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**GEORGIA INSTITUTE OF TECHNOLOGY**
OFFICE OF CONTRACT ADMINISTRATION

# RESEARCH PROJECT INITIATION

Date: October 16, 1975

Project Title: Measurement of Transport Properties of Air at High Temperatures and Pressures

Project No: E-25-660

Principal Investigator Dr. A. V. Larson/Dr. J. R. Williams

Sponsor: Arnold Engineering Development Center (AFSC); Arnold AFS, Tenn.

Agreement Period: From 10/1/75 Until 9/30/76

Type Agreement: Contract No. F40600-76-C-0004

Amount: $59,763 *

Reports Required: Monthly Progress Letters
Final Technical Report

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Assigned to: Mechanical Engineering

NOTE: Continuation of E-25-640.

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RA-3 (9-75)

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# GEORGIA INSTITUTE OF TECHNOLOGY
## OFFICE OF CONTRACT ADMINISTRATION
## SPONSORED PROJECT TERMINATION

Date: February 8, 1979

Project Title: Measurement of Transport Properties of Air at High Temperatures and Pressures

Project No: E-25-660

Project Director: Dr. A. V. Larson

Sponsor: Arnold Engineering Development Center (AFSC); Arnold AFS, TN 37389

Effective Termination Date: December 31, 1976

Clearance of Accounting Charges: December 31, 1976

Grant/Contract Closeout Actions Remaining:

NONE

- _ Final Invoice and Closing Documents
- _ Final Fiscal Report
- _ Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other ____________________

Assigned to: Mechanical Engineering (School/Laboratory)

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CA-4 (3/76)

E-25-660

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Monthly Progress Report

# MEASUREMENT OF THE TRANSPORT PROPERTIES OF AIR AT HIGH TEMPERATURES AND PRESSURES

Contract No. F40600-76-(C-0004)

Covering the period
October, 1975

Prepared by
A. V. Larson, J. A. Madill, R. T. Murray

Prepared for the

Arnold Engineering Development Center
Air Force Systems Command
Arnold Air Force Station, Tennessee

Progress Report

October, 1975

The primary goal of this work is to measure the electrical and thermal conductivities and the radiation source strength of air plasma at a pressure of 150 atm. In the previous year under contract F40600-74-C-007 the above properties were determined at 1, 6, and 30 atm.

The apparatus used for the study is a wall-stabilized, steady cascade arc. In preparation for the work at 150 atm., the entire apparatus and the pressure vessel which contains it have been disassembled and cleaned. New insulators, rubber seals, cascade plates, and electrodes have been installed. Particularly careful attention has been given toward assuring that the electrodes are symmetrically bathed with argon gas in order to reduce instabilities. The feed plenum has been enlarged and all feed tubes are symmetrically placed. All water and gas hoses have been replaced, and their clamps improved.

New quartz windows for the cascade have been chosen and their spectral transmittances have been measured using a tungsten strip lamp and a spectrometer. The transmittances of the quartz vessel windows were also measured.

The spectral radiance from two standard lamps was also compared. The relative radiance of the two lamps has changed less than 3.5% in five years even though the amount of usage has been quite different.

The thermopile and recording system have been calibrated with a blackbody source from Barnes Engineering. The source was operated at 1273°K. Both the source aperture and the distance from the source to the sensitive element of the thermopile were altered in this calibration. The measured sensitivity of 24.4 microvolt/microwatt is 2.4% below the manufacturer's data sheet which gives 25 microvolt/microwatt. The manufacturer lists the element size at 2 mm x .2 mm. The element has been examined under a calibrated microscope and has been found to have an area of 0.48 $mm^2$ which is 20% higher.

The radiation values reported in the draft copy of the final technical report for contract F40600-74-C-007 were calculated on the basis of the manufacturer's data. The calibrations at Georgia Tech require that the radiation values be lowered. Taking into account the new calibrations and considering the reflections back through the arc from windows on the side of the arc opposite the thermopile, the radiation values should be multiplied by 0.786. The values of the thermal conductivity in said report were calculated with the lower radiation values and need not be changed.

The thermal conductivity of air plasma at 6 atm. has now been deduced and is plotted in the attached graph. Also included are the data at 1 atm. and 30 atm. [Figures 20 and 21 from the draft copy mentioned above.] The points represent the average of the data from up to 11 different arc conditions. The bars represent the scatter of the individual data.

In the laboratory, the automatic feed-back regulated gas supply system has been completed. The cascade will be installed the second week of November and the experiments are scheduled to start immediately thereafter.

Mr. Jeff Madill who has worked on the project since December 1974, and who was budgeted on this contract as a Research Technician has elected to start graduate studies at Georgia Tech. He remains on the project staff and his category has been changed to Graduate Research Assistant.

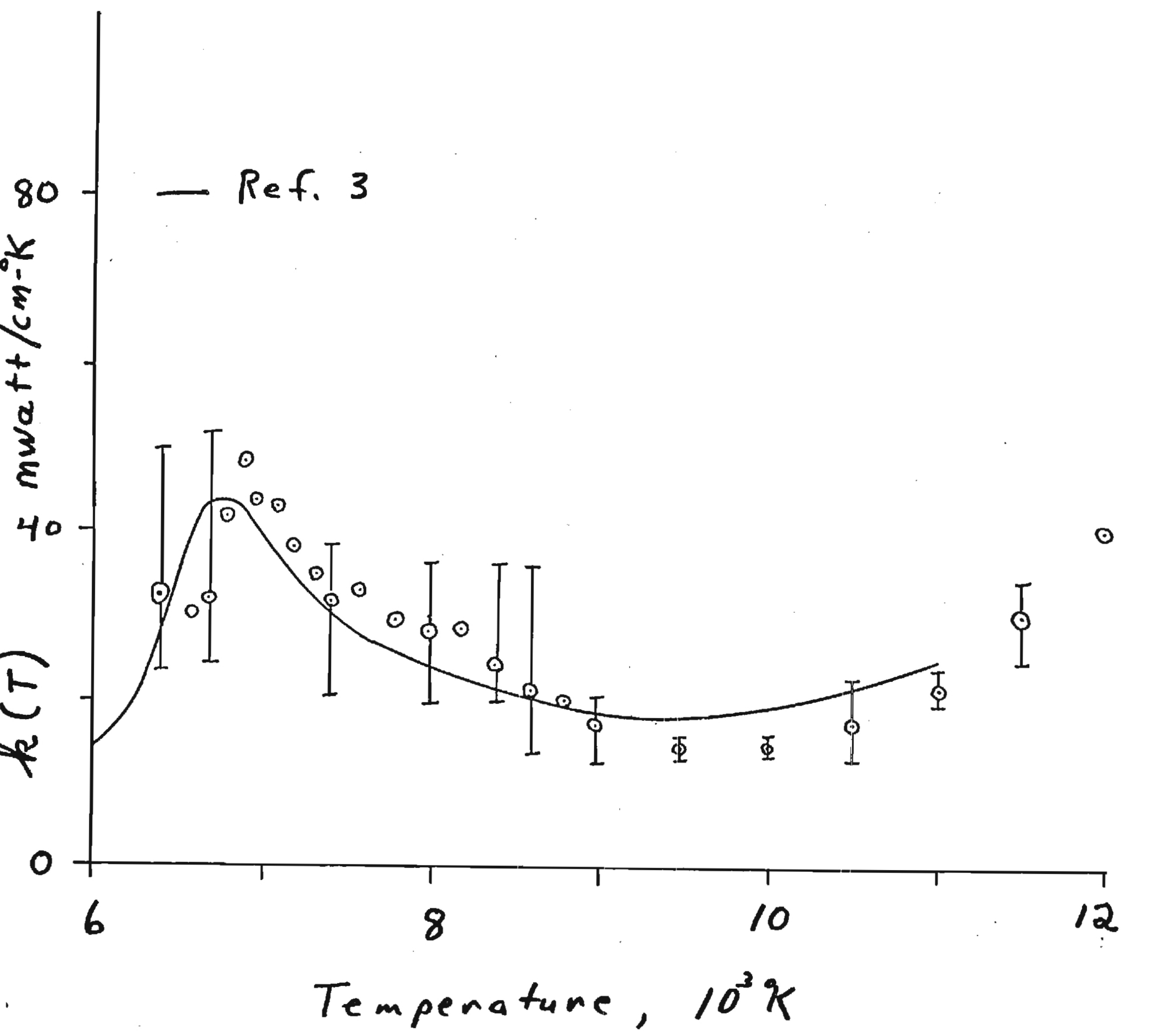
Mr. Warren Deshon, from Worcester Polytechnic Institute is starting work as a Graduate Research Assistant leading to an M.S. Thesis on the project, and Mr. Dan Dodson has started as the undergraduate team member.

Mr. Robert T. Murray has joined the staff as Research Technologist. Mr. Murray has 25 years of experience in this technology and worked with Dr. Larson at General Dynamics in California. Mr. Tinkham has left Georgia Tech to return to his home region of Southern California.

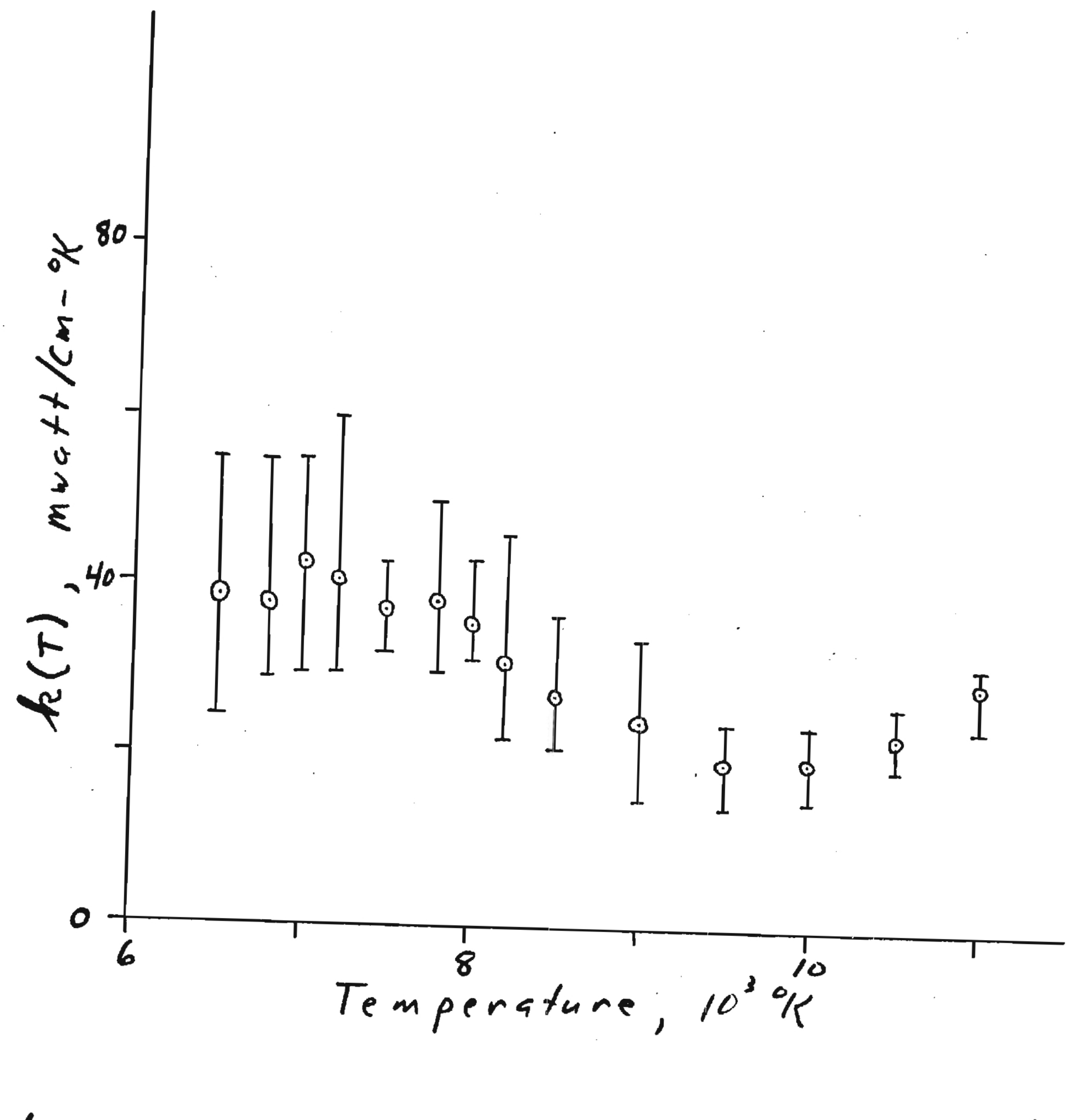
Dr. J. R. Williams, Co-Principal Investigator, has been appointed as Associate Dean of Engineering at Georgia Tech, in charge of Research. To what extent he will have to reduce his participation in this contract, Dr. Larson will increase his own participation.

The work ahead includes extending the emission coefficient library to 150 atm., finishing the data smoothing analysis of the 1, 6, and 30 atm. data, updating the knowledge of other high pressure-temperature gas data, and starting the experiments at 150 atm. The yearly calibrations are nearly finished and the experiments should start in mid-November.

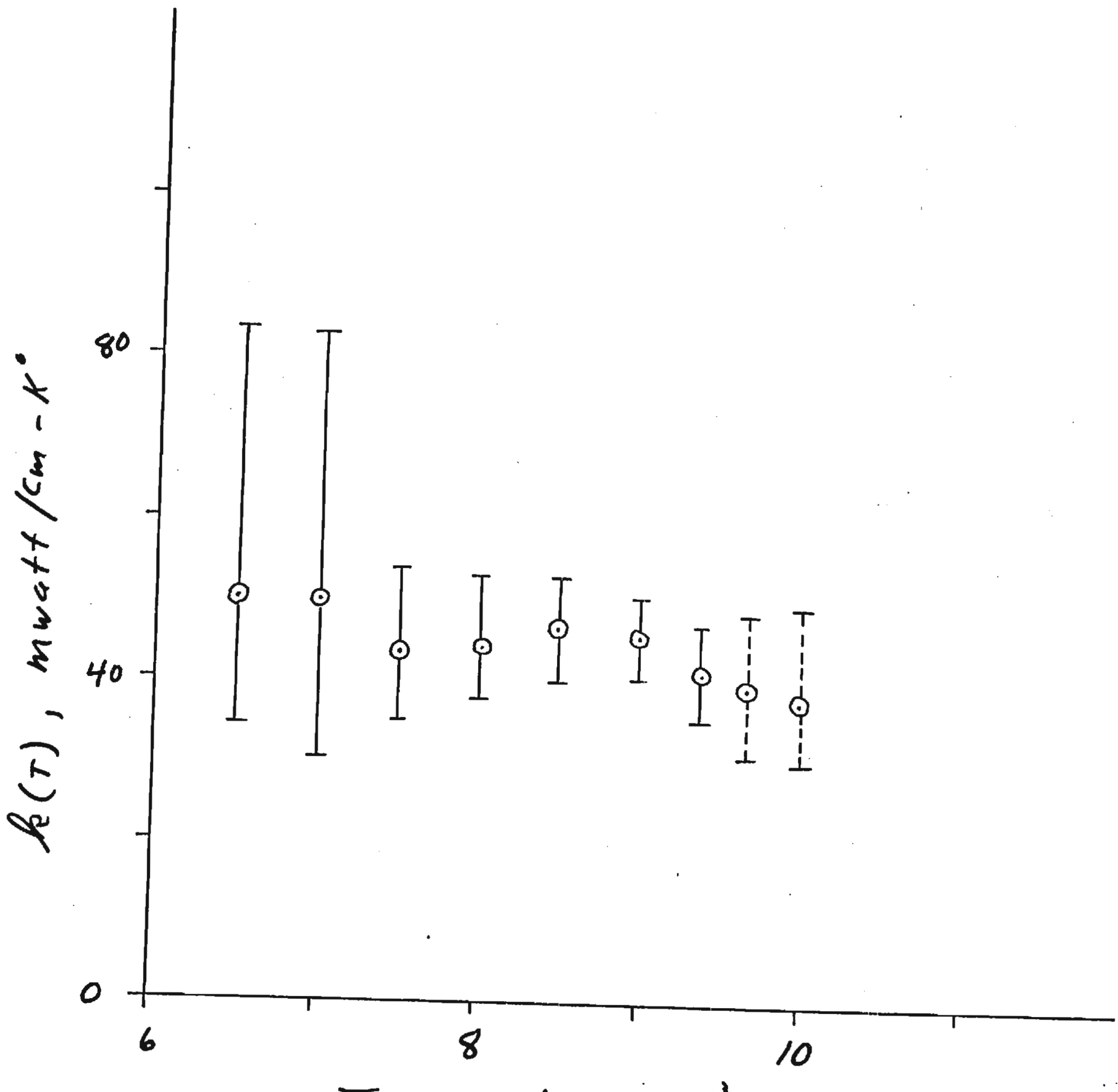
Dr. Larson is giving the paper, for which the abstract is attached, Nov. 13, at the 17th Annual Meeting of the Division of Plama Physics, American Physical Society, St. Petersburg, Florida. The announcement appears in the Bulletin of the American Physical Society, October 1975. This year there will be 963 papers, up from 619 in 1972.




20.) Thermal Conductivity of Air Plasma at 1 Atm.




Thermal Conductivity of Air Plasma at 6 Atm.




) Thermal Conductivity of Air Plasma at 30 Atm.

sion coefficient, $D \sim n^{\delta}B^{\gamma}e^{-\beta t/\tau}$ where $\delta$, $\gamma$, $\beta$, and $\tau$ are variable parameters, leads to separable time and profile shape equations. Fitting experimental profiles shapes and time evolution to the model allows determination of the scaling of the diffusion coefficient with density, temperature, and magnetic field. The model has also been extended to apply to a time varying magnetic field taking into account particle transport due to field line motion.

*Work supported by U. S. ERDA
+Submitted by J. C. Sprott

8G8 Temperature-Related Profile Shapes With a Weak Toroidal Field,* J. R. DRAKE, Univ. of Wisconsin--Density profiles of a collisionless, warm ion plasma in an octupole field were affected by the addition of a weak toroidal field in a manner which suggested trapped ion effects may have been involved. Starting with a cold-ion ECRH-generated plasma, the ions were heated to about 20 eV. Before heating the ions, the pressure profile was peaked inside the separatrix both with and without a toroidal field. Heating the ions did not change the profile shape when no toroidal field was present. But with a weak toroidal field, the plasma quickly relaxed to a separatrix-peaked shape. With the toroidal field, the warm ions in the inverted gradient region would be unstable to the low-frequency interchange instability.[1] The azimuthal velocity of transient ions streaming along the field line helix would be greater than the azimuthal drift of the trapped particles, yet the drift would be adequate to support profile-altering instability growth rates on the time scales observed.

*Work supported by U.S. ERDA
[1]M. N. Rosenbluth, Phys. Fluids 11, 869 (1968).

8G9 Observation of Diffusion Coefficient Scaling in the Wisconsin Levitated Octupole,* G. A. NAVRATIL and R. S. POST, Univ. of Wisconsin--The scaling of an experimentally observed diffusion coefficient with magnetic field, density and electron temperature was studied in the Wisconsin Levitated Octupole. The flux of particles lost to the surface of an internal ring could be measured directly using striped particle collectors[1] or inferred from the observed density decay. The magnetic field could be varied between 100 Gauss and 2.5 KGauss. Gun injected hydrogen plasmas were produced in the density range of $10^8$ to $10^{12}cm^{-3}$. $T_e$ was ~ 1 eV but could be adjusted in the higher density plasmas by off resonance microwave heating up to ~ 6 eV. In the low density range, $10^8$ to $10^9cm^{-3}$, D was found to be independent of B and proportional to $n^{-x}$, where $x = 0.6 \pm 0.2$. In the higher density plasmas, $10^{10}$ to $10^{11}cm^{-3}$ D was also independent of B and proportional to $\sim T_e$ when $T_e \geq 3$ eV.

*Work supported by U.S. ERDA
[1]D. E. Lencioni and D. W. Kerst, Bull. Am. Phy. Soc. 15, 1466 (1970).

8G10 Charge Exchange of Protons on Methane Neutrals Affects Ion Energy Decay and Ion Purity.* R. BREUN, U. Wisconsin—In the large toroidal octupole confinement device, Marshall gun produced proton plasmas with densities ($n_i$) of $10^9 cm^{-3}$ and ion temperatures ($T_i$) of 20-30eV were found to have their energy decay times dominated by only $5x10^9 cm^{-3}$ of methane neutrals. The proton interaction with methane neutrals was positively identified as charge exchange by the observance of cold methane ions. A momentum and an energy analyzer were used to detect both the mass and energy of the ions. The decay of hydrogen ions within the ion distribution was measured for various methane neutral densities, and the cross section thus derived ($\sigma \sim 4x10^{-15} cm^2$) compared favorably with tabulated charge exchange cross sections of protons on methane. Using this cross section, the ions were theoretically estimated to be 50% methane ions after only 7ms for the initial conditions above. A $10^{\circ}K$ cold plate was introduced to reduce this effect for norma l diffusion experiments.

*Supported by ERDA.
1 D. W. Koopman, Journ. of Chem. Phys. 49, 5203 (1968).

8G11 Air Plasma Transport and Radiative Properties at Pressures from 1 to 30 Atm. A. V. LARSON, J. R. WILLIAMS, Georgia Inst. of Tech.—A wall-stabilized steady cascade arc provided a cylindrically symmetric column of air plasma. The electrodes were bathed in argon. The electrically floating wall plates were used to determine the electric field strength in the column. Side-on optical measurements of the lateral intensity profile using the oxygen 8446.5 A line and the nearby continuum permitted the deduction of the radial temperature profile using the Abel Inversion. Total radiation per unit length for wavelengths transmitted through a quartz window was measured by a thermopile. Arc currents were varied from 8 to 40 amps. Data was taken at pressures of 1, 6, and 30 atm. Trial functions of electrical conductivity and radiation strength per unit volume both dependent upon temperature were optimized by computer to fit the experimental data. Thermal conductivity was then obtained from the energy balance. The data lies in the temperature range from 6500 to 10000 °K. The atmospheric properties agree well with the literature.

Supported in part by Arnold Engineering Development Center, Tennessee, Contract No. F40600-74-(C-007)

8G12 Neutral Density in a Hydrogen Arc.* † W.J. GOEDHEER and G.G. LISTER, FOM-Instituut voor Plasmafysica, Jutphaas, The Netherlands.-- Earlier work on the energy balance of a hydrogen arc by Verboom[1] has been extended towards lower pressures (wall pressure ∿ 1 torr). To make this extension, the concept of a local thermodynamic equilibrium is dropped and the SAHA equation is replaced by a set of rate equations, which describes the population densities of the atomic levels of hydrogen. The neutral density profile, the energy balance, and the pressure balance are compared with the SAHA case. Voltage-current characteristics, temperature and pressure profiles are obtained for arcs with a fixed radius and wall pressure. An attempt is made to include in the deviations from LTE the effects of ambipolar diffusion in the arc.
*Submitted by J. REM.
†Supported by the Euratom-FOM Association.
[1]G.K. Verboom, Plasma Physics 11, 903 (1969).

8G13 Plasma Confinement in the Tormac IVA and Tormac IVB Devices.* M. A. LEVINE, B. R. MYERS, I. G. BROWN, Lawrence Berkeley Laboratory.--Experimental results from the Tormac IVA and Tormac IVB toroidal line cusp devices are presented. Plasma densities of $10^{15}$- $10^{16}$ $cm^{-3}$, as measured by a laser interferometer and by stark broadening of Hβ, are achieved and indicate stable plasma confinement for the duration of the 4 kg. containment field (~100 μsec). Spectroscopic plasma temperature measurements and Shaker[1] heating results are discussed. Image converter photographs of the plasma production, compression, and confinement phases in Tormac IVB are shown. Plasma shape in the confinement phase agrees with the shape predicted by the electrolytic tank measurements used for designing the containment field coils.[2]

*Work supported jointly by the Electric Power Research Institute and by US ERDA.
1. M. A. Levine, C. C. Gallagher, and A. H. Boozer, Bull. Am. Phys. Soc., 19, 9, 928 (1974).
2. L. S. Combes, C. C. Gallagher, and M. A. Levine, Rev. Sci. Inst., 37, 1567 (1966).

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GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Monthly Progress Report

# MEASUREMENT OF THE TRANSPORT PROPERTIES OF AIR AT HIGH TEMPERATURES AND PRESSURES

Contract No. F40600-76-(C-0004)

Covering the period
November, 1975

Prepared by
A.V. Larson, R.T. Murray, Staff
J.A. Madill, W. Deshon, D. Dodson, Students

Prepared for the

Arnold Engineering Development Center
Air Force Systems Command
Arnold Air Force Station, Tennessee

Progress Report
November, 1975

Experiments were resumed on Nov. 20th using the automatic feed-back regulated gas supply system and the improved cascade arc apparatus. The initial goal is to demonstrate proper arc operation at 100 atm. with an air test section and electrodes bathed with argon. About 15 hours of running time have been accumulated on the new apparatus.

The arc is started in pure argon at 1 atm., 15 amp. and then pressurized before fully admitting air to the test section. Several trials were necessary to establish a good procedure to achieve control of the air at 100 atm. The resulting method is a) check out the argon arc at 1 atm., setting the proper pressure differentials for the argon and air flows for successful operation at 1 atm., b) open the air needle valve to the smallest setting for which air is just evident in the test section, c) increase the chamber pressure while allowing the automatic system to maintain the correct pressure differentials in the flow lines. The advantage of the procedure is that pure air is established prior to and maintained during pressurization in the air plenum and lines which feed the test section.

The initial efforts to find a good procedure failed because 1) the arc was blown out when the air was admitted at 100 atm., or 2) the air arc was not under sufficient control to avoid wall damage, or 3) the argon had flown backward into the air plenum and lines thus making it difficult to interpret the effect of changing the air valve and regulator settings.

With the correct procedure, each of the above problems has been avoided. The precision motorized needle valves allow a sensitive fine-control of the air input. For example, starting with nearly pure argon (no indication of the OI 8446 line) the electric field strength is about 42 v/cm. The air needle valve can be opened in steps so that the electric field strength advances at most 3-4 v/cm. With pure air, initial indications are that values of 80-100 v/cm will be reached.

We tried at first to aviod repeating any work at 6 and 30 atm, but since the air entry at 100 atm. proved difficult, some work at 6 and 30 atm was repeated. With the improved system, at 30 atm. the pure air arc was much easier to establish and far more stable than heretofore. (Work at 1 and 6 atm. had become routine a year ago.) This is a positive finding because of the AEDC interest in air properties at modestly higher temperatures than have been measured so far.

In proceeding from 30 atm. to 100 atm. a change in the apparatus was noticed which is best described with reference to Figure 1. The plates in the test section are insulated from each other by gas seals. At each end two seals are removed which allow "breather ports" for the removal of the mixed air-argon. The four breather ports and the central port are imaged at the spectrometer. The images are important in arc control since the air and argon columns are typically of different colors and diameters. In proper operation, the images of the extreme outer ports indicate nearly pure argon, the central image is that of pure air, while the other two indicate a mixture of the gases.

As the pressure was increased from 30 to 100 atm., the images of the extreme outer ports disappeared. Either their rays failed to exit the pressure vessel window or no longer could pass through the lens stop. Since the pressure differentials are small within the chamber, the cause would seem to be stress within the pressure vessel window. The cause has not been sought yet.

The immediate result of the loss of the two images was to cause conservation in the experiments. Since we could not tell how far the air had advanced toward the electrodes, we elected to keep a lot of argon in the nearer breather ports. Pure air could not be achieved in the test section as a result of this decision. What spectral data that might be of value was taken and the run was terminated to correct the image loss problem.

The image loss problem can be corrected by installing a simple periscope system at each end of the cascade to make certain the ports are imaged at the position of the spectrometer as usual.

Of greater consequence is the implication that the magnification and linearily of the optical system will have to be measured at the operating pressure. No major problem is anticipated in this calibration.

The initial spectral data is given in Figures 2 and 3. In Figure 2, the spectrometer is changed by hand to look at the argon 8424 and oxygen 8446 lines as the air is introduced in larger and larger amounts. One sees a decrease in the argon line and an increase in the oxygen line. Purity of air was not achieved, but from past experience at 30 atm. once this state had been achieved, it was always possible to go further and obtain air purity.

In Figure 3, a wavelength scan of the radiation from the arc center is recorded. The scan was motorized: The abscissa is linear in wavelength. Again purity is not evident. However it looks as if line broadening is not too severe, and that the line to continuum (8450 - 8470, not shown) ratio is still high. Furthermore we expect the signal level of the O8446 line at air purity to be more than adequate.

In conclusion, the initial results at 100 atm. are encouraging. The new gas-control system appears to have been designed with enough control sensitivity. The 100 atm. argon arc appears to be quite stable. As air is introduced, the test section turns first pale yellow, then bright orange while the two nearest breather ports remain bluish white. The visual colors, the spectrum, and the field strength indicate that air purity has almost been achieved, but the latter two show that argon is still within the test section. The initial spectrum has not revealed any spectroscopic difficulties.

In December it is planned to inspect and clean the cascade arc, replace the cathode, install the mirror system within the pressure vessel, and resume the experiments around Dec. 6-9. Also, as Schlieren effects are now evident at 100 atm. due to the gradients in the gas between the cascade apparatus and the pressure vessel wall, baffles or quartz rods will have to be introduced to minimize these effects.

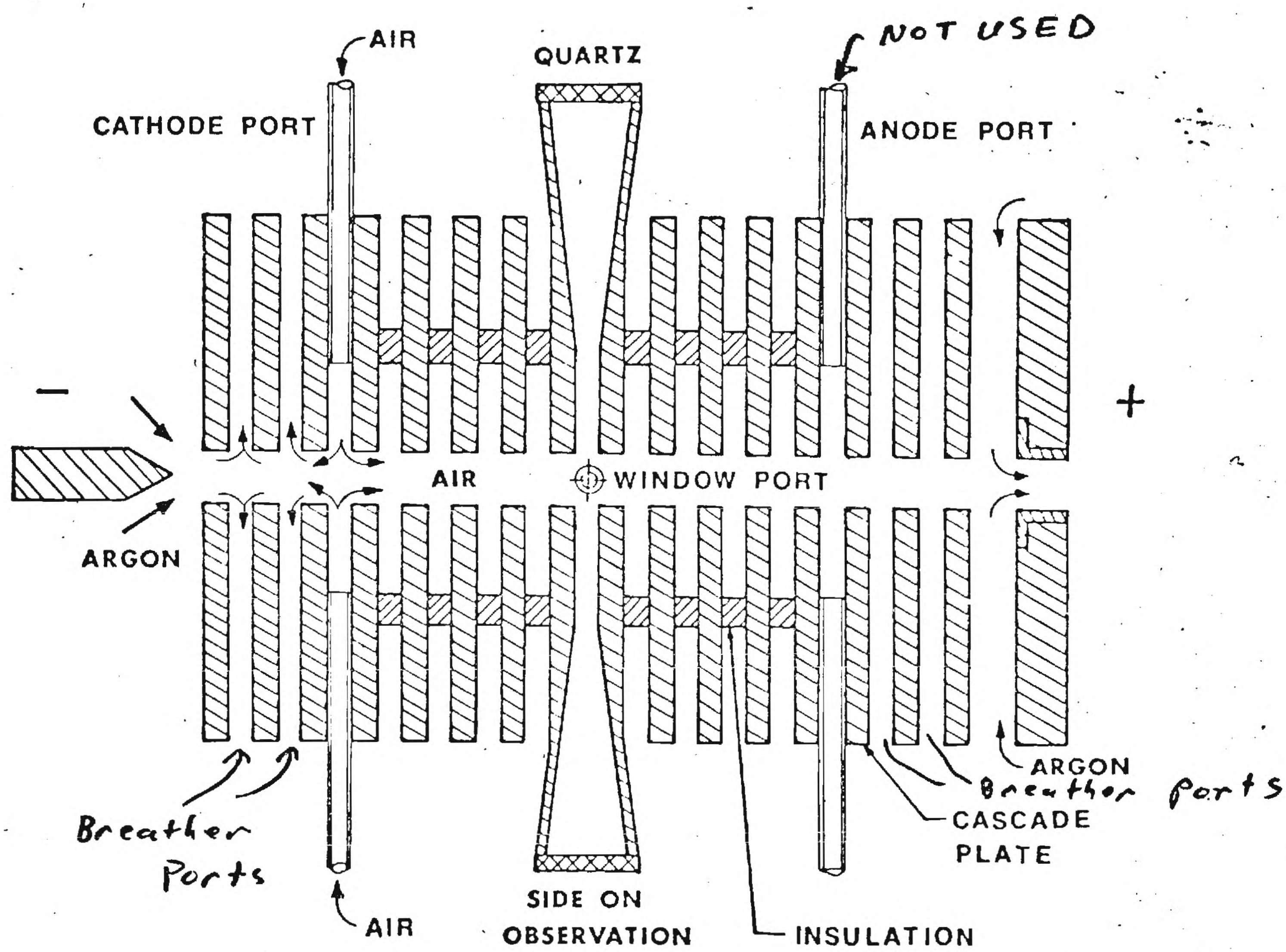



Figure 1. Schematic Diagram of Arc Apparatus

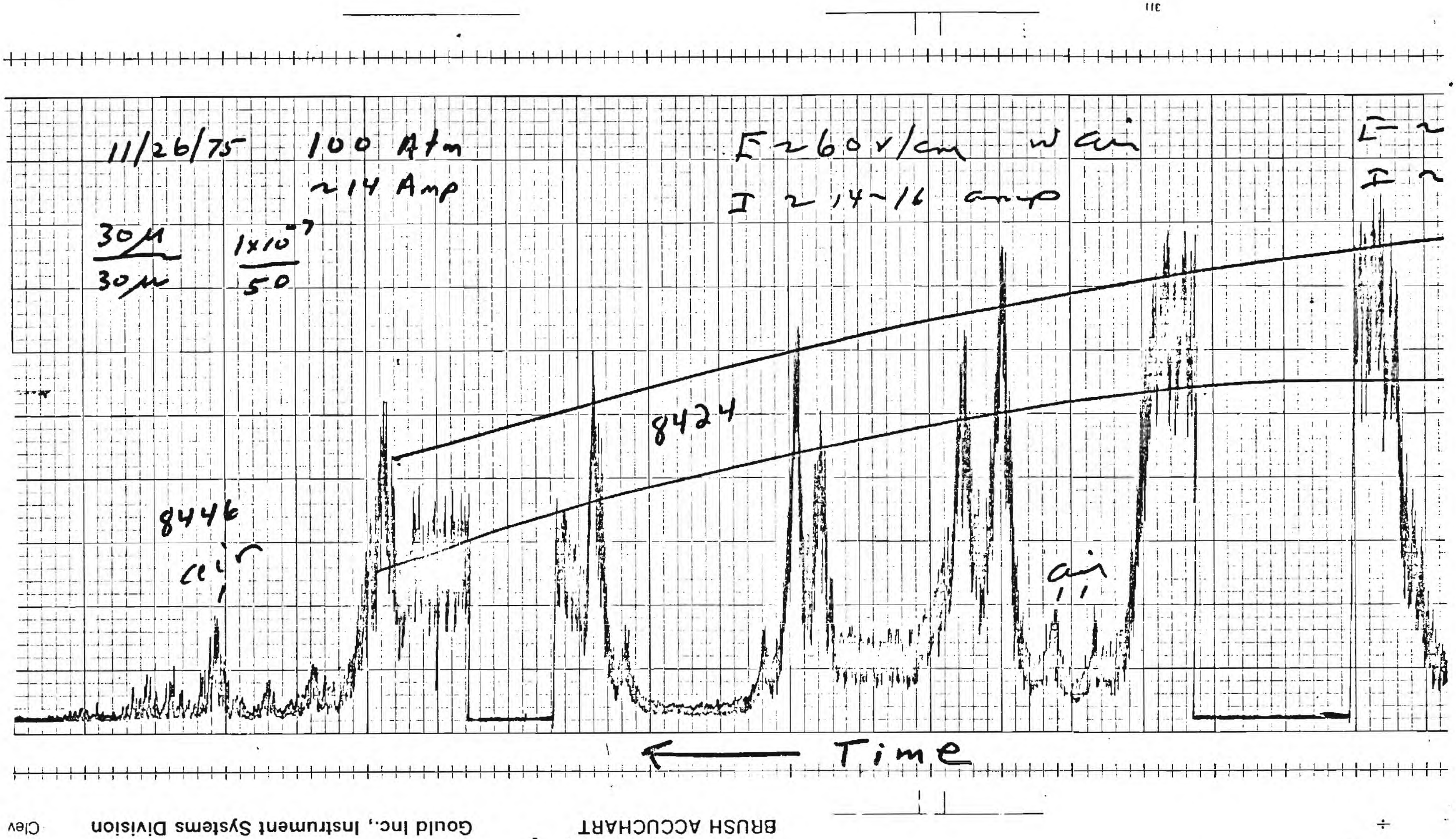

11/26/75
100 Atm
~14 Amp
30μ
30μ
1x10^-7
50
E ~ 60 v/cm w air
I ~ 14~16 amp
8424
8446
air
air
Time

Fig 2.

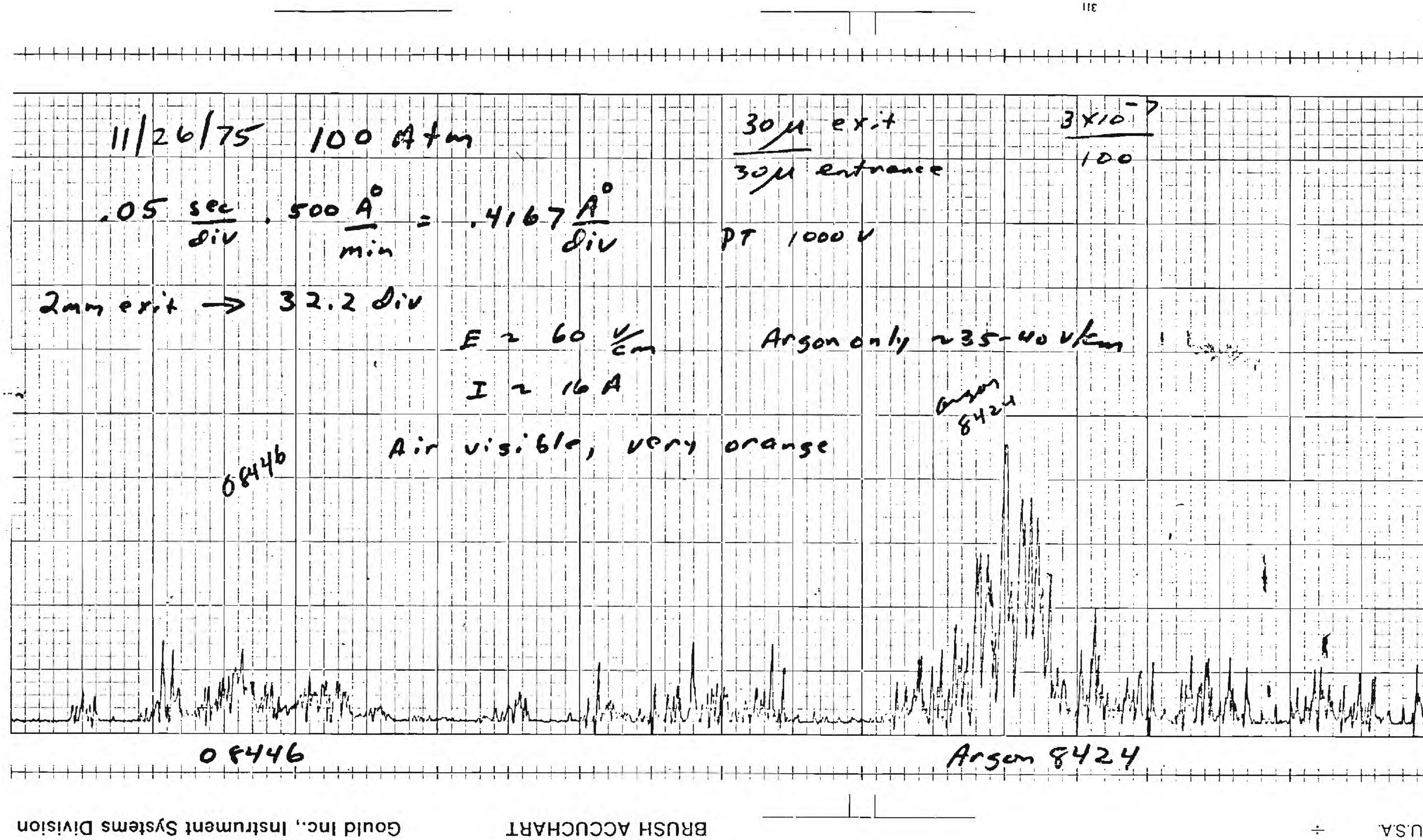

11/26/75 100 Atm
30μ exit
30μ entrance
3×10⁻⁷
100
.05 sec/div · 500 Å/min = .4167 Å/div
PT 1000 V
2mm exit → 32.2 div
E ~ 60 V/cm
Argon only ~35-40 V/cm
I ~ 16 A
Argon 8424
Air visible, very orange
O 8446
O 8446
Argon 8424
Gould Inc., Instrument Systems Division
BRUSH ACCUCHART
U.S.A.

Fig. 3.

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Monthly Progress Report

# MEASUREMENT OF THE TRANSPORT PROPERTIES OF AIR AT HIGH TEMPERATURES AND PRESSURES

Contract No. F40600-76-(C-0004)

Covering the period
December 1975-January 1976

Prepared by
A. V. Larson, R. T. Murray, Staff
J. A. Madill, D. Dodson, Students

Prepared for the

Arnold Engineering Development Center
Air Force Systems Command
Arnold Air Force Station, Tennessee

Experiments were resumed in mid-December. The loss of the images of the breather ports farthest from the observation window (see Figure 1) as chamber pressure increased was found to be due to an expansion of the rubber gasket in the vessel window assembly. Trimming the gasket and installing glass periscopes within the vessel to move the images from the breather ports closer to the arc midplane eliminated the image loss problem.

As reported in November '75, the lack of information about conditions near the electrodes resulted in conservatively holding the air away from the end regions at the cost of being unable to obtain air purity in the test section at 100 atm. Upon disassembly to fix the image loss problem, it was found that the electrodes were in excellent shape.

When the experiments were resumed in mid-December, all port images were observable at 100 atm. The air flow was increased and as is usual, the degree of purity increased in the test section, and the air column advanced toward the electrodes. The region near the cathode was hard to control which led to plate erosion and arc shut-offs. After many tries the proper balance between the air flow and the argon flow near the cathode was achieved in mid-January. In the same run during which the cathode region was under control, complete air purity in the test section was impossible to achieve even though the air and argon flows could be manipulated over a wide range. Neither a faulty gas-seal nor a broken feed line was suspected because purity and stability could still be achieved at 30 atm. Suspecting instead gas mixing from a variety of possible flow problems, we elected to establish purity and stability at 30 atm. and then to increase pressure while maintaining purity and stability. This procedure was successful up to 50 atm. Since the arc current had dropped with increasing pressure to 10 amp. and the electric field strength had risen to 90-100 volt/cm, it was decided to drop the field strength by increasing the current. As additional current was switched in, it triggered an instability which terminated the run. Upon inspection, one of the four small air feed tubes was found to be broken, probably by the hot gases from the breather ports. The effect was sufficient to prevent the attainment of air purity at 100 atm., but not at 50 atm. [The pressure charging techniques were different in going up to 100 atm. and 50 atm., but the significance of this is unknown].

The plastic air feed hoses have since been replaced by stainless steel tubing. After repair, the pure, stable air arc was again established at 30 atm. In going to higher pressures, the original technique was resumed. The air flow was cut to just a trace (in order to keep pure air in the air plenum) before the argon chamber pressure was increased to 50 atm. A stable, pure air arc at 50 atm. was easily and quickly established in this manner. Again the air flow was cut to a trace and the chamber pressure increased to 75 atm. As the air was being brought back to establish purity at 75 atm., the arc jumped the channel in the test section, and one plate delaminated slightly, allowing a small water leak.

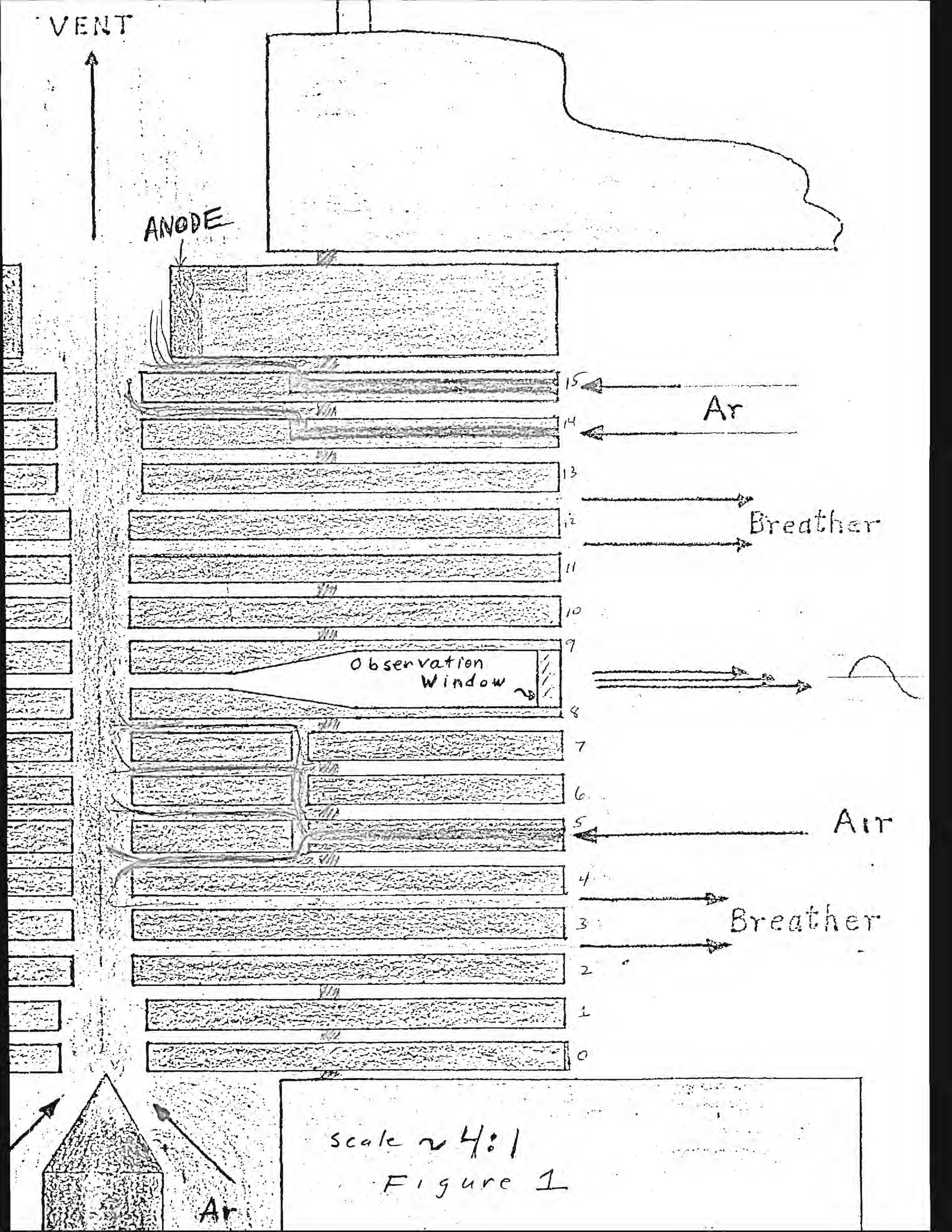
To summarize our experience so far: An excellent, pure air, stable arc can be easily and quickly established at 50 atm. using either of two pressure charging techniques. Since the goal is to achieve the same at 150 atm., detailed data has not been taken at 50 atm. However, the arc characteristic and the total radiant power were obtained and are shown in Figures 2 and 3, respectively.

At 100 atm. the arc was quite stable for two hours, at near purity, although complete purity was not possible because of the broken air hose. It is hoped that the success at 50 atm. can now be extended to 100 atm. with the repaired apparatus.

The recent failures of the apparatus have been characterized by two events: The arc jumps out of the channel and through the plates, and secondly, one of the plates springs a water leak at the bore. The sequence of the events is unknown. To minimize the chances of a water leak, plates will be chosen which have a larger bonded area between the bore and the water passages.

A glance at Figure 2 indicates that the electric field strength may be approaching values high enough so that the transfer of the arc to the walls becomes highly probable. To reduce the field strength, a 4mm bore can be selected, but only at the risk of increasing arc wobble.

The present configuration is shown in Figure 1 with approximately a 4:1 scale. Schlieren effects in the images of the ports and observation window, due to gradients in the gas between the arc apparatus and the wall of the pressure vessel, become noticeable at 45 atm. By installing a metallic shroud, carefully sealed at the observation window, and extending toward the vessel window, the Schlieren effects in the image at the spectrometer have been eliminated up to at least 100 atm.




scale ~ 4:1
Figure 1

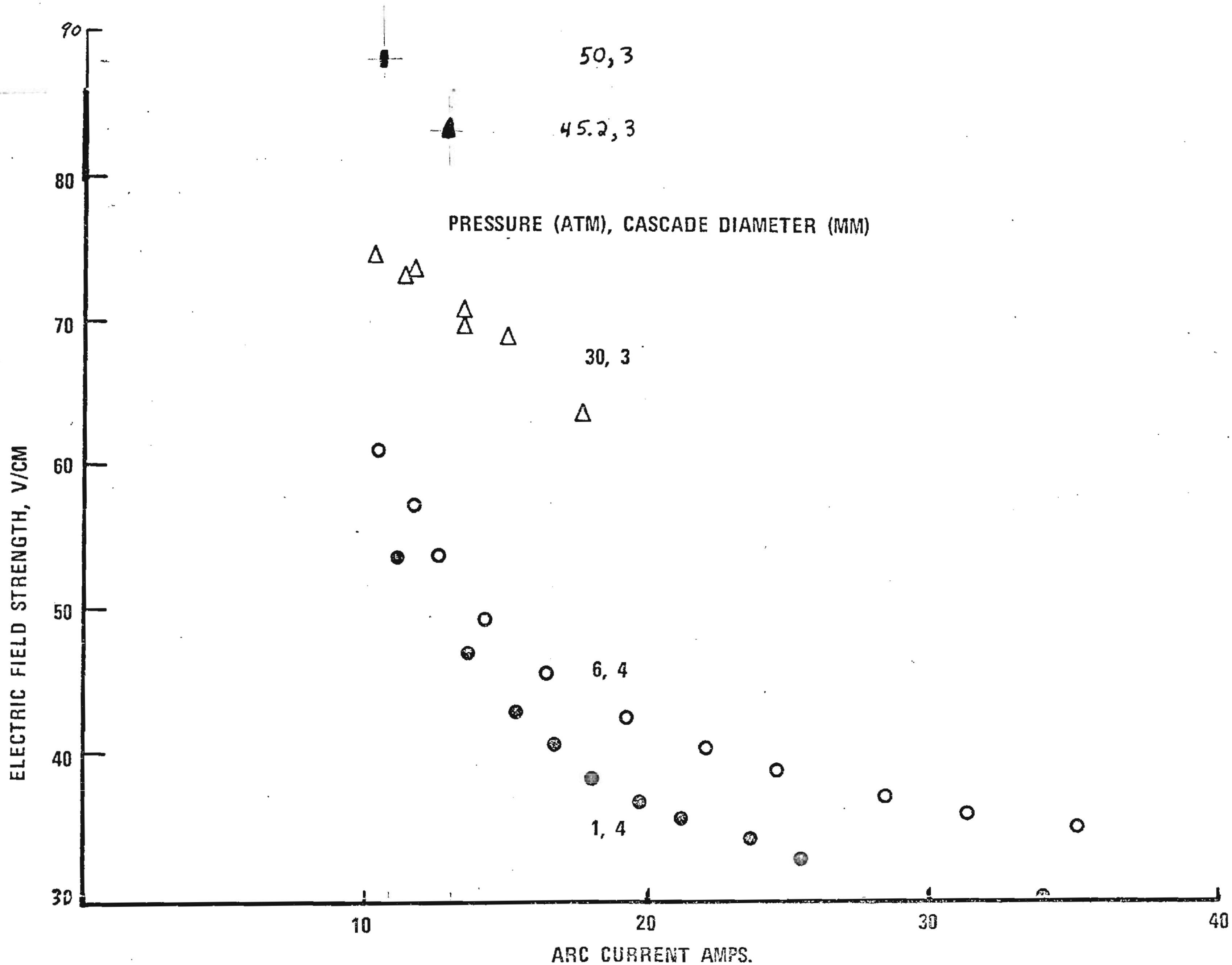



Figure 2. Arc Characteristics E (I, P) for Air.

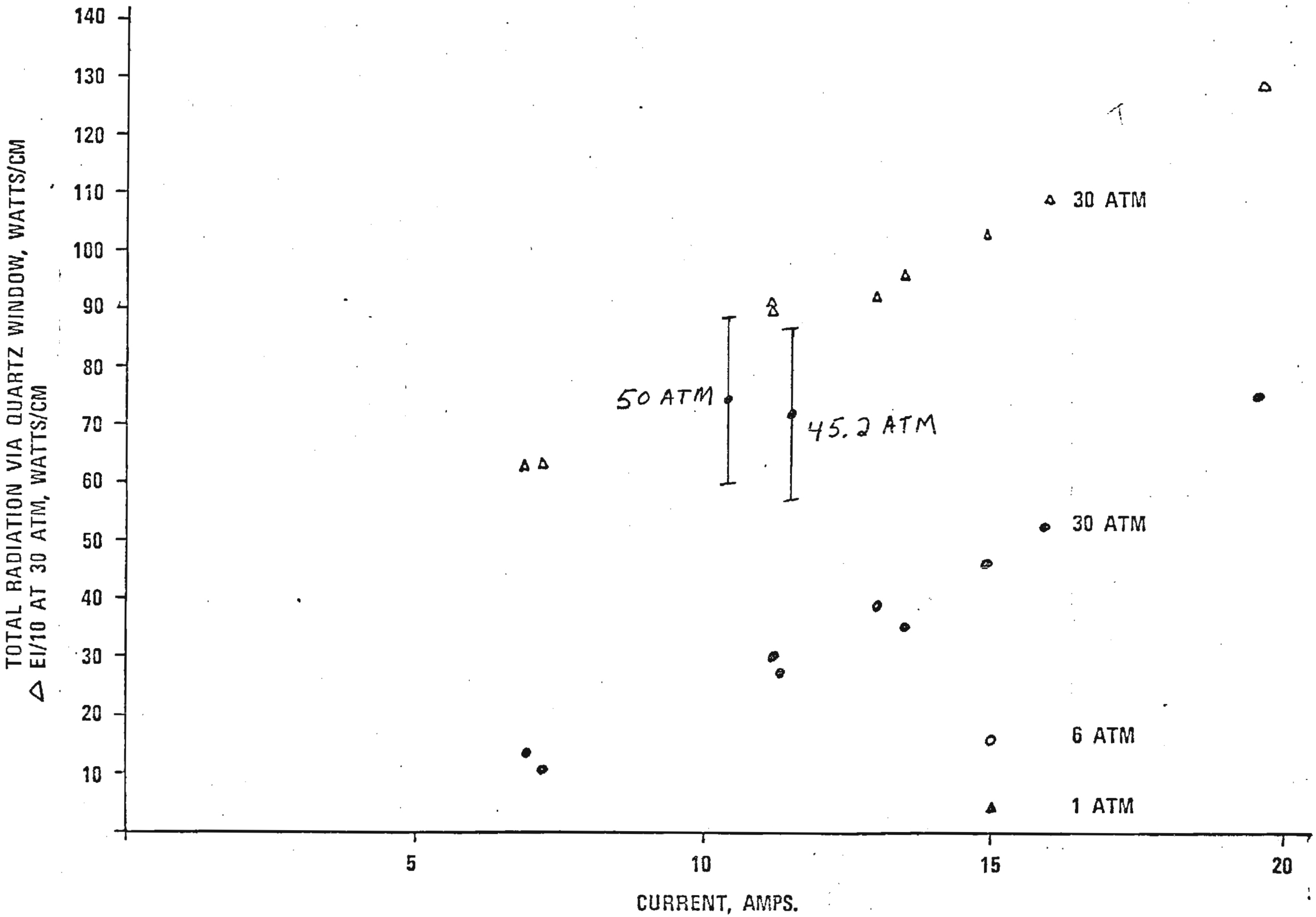



Figure ~~II~~ 3. Radiation of Air Arc vs. Current and Pressure.

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Monthly Progress Report

# MEASUREMENT OF THE TRANSPORT PROPERTIES OF AIR AT HIGH TEMPERATURES AND PRESSURES

Contract No. F40600-76-(C-0004)

Covering the period
February, 1976

Prepared by
A. V. Larson, R. T. Murray, Staff
J. A. Madill, D. Dodson, Students

Prepared for the

Arnold Engineering Development Center
Air Force Systems Command
Arnold Air Force Station, Tennessee

## Progress Report

A number of advances have occurred since the last progress report. Several runs have been made on pure air arcs at arc pressures of 75 and 100 atm. and additional data has been taken at 50 atm. The first results on the total radiation from air arcs operating above 50 atm. are encouraging from the point of view of the goals of the AEDC air-heating projects. Technologically, it has been possible to reduce considerably the amount of running time on the apparatus which is required to establish a pure air arc column at 100 atm. Finally, the more expensive arc failures caused by plate delamination and the subsequent water-related damage occur far less frequently with the new bore design.

### DATA

The evidence for the purity of the central arc column at 100 atm. is shown in Figure 1 where a spectral scan over the approximate wavelength range 838 to 852 nm is shown. The oxygen 844.7 nm line radiation is identified and the location of two strong argon lines is shown. When the channel is pure argon, the two argon lines have peak intensities about six times greater than the oxygen line shown in Figure 1 and widths comparable to that line.

For the data of Figure 1 the center of the image of the arc was set on the spectrometer entrance and the ratio of arc diameter to entrance slit width was about 120. The bandpass of the exit slit was set at .067 nm (.4 small division on the chart). The maximum bandpass of the exit slit is 1.34 nm (8 small divisions on the chart). Since the present slits do not pass all of the line radiation, for work which involves the total line radiation, wing correction formulas or the use of larger exit slits will have to be investigated.

In previous work at or below 30 atm., the continuum was measured at 847 nm and subtracted from the radiation near 844.7 in order to obtain the line radiation. Figure 1 shows that the correction due to the continuum will be small. However, if the spectrometer exit slits are set wide enough to pass all the line radiation, then the continuum should be measured near 849 nm in order to avoid overlapping the line radiation.

After air purity at 100 atm. was established, the lateral intensity profiles shown in Figure 2 were taken. The spectrometer entrance and exit slits remained the same, and the image of the arc was swept across the spectrometer entrance slits at a constant rate. Had the signal represented the total line radiation, temperature profiles could be deduced easily from the data. However, one does learn from the width of the profile that the diameter of the arc over which the temperature is above 6000°K is about 1.7 mm.

The high frequency component in Figures 1 and 2 is due to some combination of a slight physical wobble of the arc, transients in the electric field strength, or other causes. In the past it has been possible to reduce this component by careful adjustments of the arc conditions.

The arc parameters for Figures 1 and 2 were:

| | | |
|---|---|---|
| voltage | 536 | volts |
| current | 10.0 | amps |
| electric field strength | 110 | v/cm |
| channel bore diameter | 3.0 | mm |

The arc column was prepared by starting the arc in argon at 1 atm and about 15 amp. Air purity was then established at 1 atm after which the air flow was cut to a trace. This procedure checks out the flow system and maintains purity in the air plenum as the vessel pressure is increased. At 50 atm., the pure air arc column was established and again the air flow was cut to a trace. Ditto at 75 atm. At 100 atm. air purity was established and the data of Figures 1 and 2 were taken. The new data on the arc characteriestics measured under this procedure are shown in Figure 3 (circles with vertical bars) along with previously reported data. The electric field strength in the table above is slightly less since there was a gradual drift downward as the run continued.

The new data plotted in Figure 3 is given in the table below along with the power input per cm.

| P(atm) | I(amp) | E(v/cm) | EI(watt/cm) |
|---|---|---|---|
| 50 | 13.8 | 89 | 1228 |
| 75 | 11.9 | 97 | 1154 |
| 100 | 10.0 | 115 | 1150 |

The changes above result from simply increasing the arc pressure. Note that the arc adjusts while staying approximately at constant input power in the air column. Since theory (1) suggests that the thermal conductivity increases with pressure between 10 atm. and 100 atm, the above data indicates that the arc center runs cooler as pressure is increased. The last clause must be qualified by statements as to the relative amounts of radiation from the arc.

In the above experiment and others similar to it at Georgia Tech, it has been found that the total arc radiation (for $\lambda$ between .3 and 11$\mu$) decreases as pressure increases. This is understandable if the arc is cooler, but there are other possible explanations related to the rate of change of of radiative power with respect to pressure at constant temperature.

The observation has not been quantitatively explained for want of a temperature profile. Noting the high field strength at 100 atm., it was decided to increase the current in an attempt to lower the field strength. Switching more current in,caused the arc to jump out of the channel, terminating the experiment.

The analysis can proceed somewhat further without knowledge of the temperature if one uses average values. Then

$$I = 2\pi E \int_0^R \sigma \, r dr = \pi E \bar{\sigma} R^2$$

where R is a radius outside of which little current flows and $\bar{\sigma}$ is the spatial average of the electrical conductivity. From Figure 2, let R = 1.7 mm. Using values of I, E appropriate to Figure 2, one obtains

$$\bar{\sigma} = \frac{I}{\pi E R^2} = \frac{10}{\pi \times 110 \times .0289} = 1.00 \text{ mho/cm}$$

Using the form of the temperature profile found in experiments below 30 atm. and using the theoretical values for $\sigma$ at 100 atm. in Figure 4, it is estimated that the temperature on axis is about 9000°K. Thus as a crude comparison, one can relate the total radiation from this arc to that from arcs at 30 atm. with $T_{axis} \cong 9000$°K, in order to estimate the dependence of radiation upon pressure at constant temperature for pressures between 30 and 100 atm.

The interesting comparisons can be made on the data in the table below.

| P(atm.) | $T_A$(°K) | I(amp) | E(v/cm) | EI(w/cm) | $P_r$(w/cm) |
|---|---|---|---|---|---|
| 30 | 8,972 | 10.18 | 74.5 | 758 | 22.6 |
| 30 | 9,130 | 11.28 | 72.6 | 819 | 27.2 |
| 30 | 9,327 | 11.69 | 73.6 | 860 | 28.9 |
| 30 | 9,587 | 13.07 | 70.4 | 964 | 35.9 |
| 91 | - | 16.2 | 112.4 | 1821 | 32.7 |
| 100 | - | 10.0 | 110 | 1100 | - |

The axis temperature $T_A$ and the power radiated per unit length through quartz windows $P_r$ are included along with the arc characteristics.

The striking feature is that the radiation per unit length is only 3-4% of the input power at 30 atm. and less (1.8%) at 91 atm. It was argued above that $T_A$ at 100 atm was ~9000°K, an estimate which decided the particular choice of the 30 atm. runs. Since one would expect $T_A$ for the 91 atm. arc to be greater than $T_A$ for the 100 atm. arc, and that $P_r$ would increase as $T_A$ increases, one can draw the tentative conclusion:

1. Radiative losses relative to electrical input power of air plasma near 9000°K are small (2 to 4%) at 30 atm. and 90 atm.
2. Absolute radiative losses at comparable temperatures are comparable at 30 atm. and 90 atm.

The verification of the tentative conclusions above requires more data, in particular the arc temperature profiles under various conditions. The project is now concentrating on acquiring the data required to deduce the temperature.

## Technology

In the last report, arc failure modes at high pressure were reported in which the arc jumped out of the channel and a cascade plate delaminated causing a water leak at the bore. The sequence of events was unknown. Since then, the bonding surface area between the bore and the water channel has been increased. The minimum radial distance between the bore and water channel was increased from .5 mm to 1.5 mm. Subsequently, there have been no further delaminations.

However, the arc continues to jump out of the channel, or to extinguish. If an observer sees this event soon enough and shuts off the power, there is no damage, and the arc may be restarted. The arc jumping out of the channel suggests that the field strength is too high whereas the arc extinguishing may suggest that the temperature is too low. The remedy for the latter is to increase the current. As Figure 3 reveals, one might expect an increase in current also to lower the field strength. However, the data at 30 and 50 atm. indicate that E(I) flattens out at higher pressure. More data, not shown, also gives a flat curve, within scatter, at 100 atm. between 8 and 15 amps. The experiments at 100 atm. have been in this interval so far.

An important advance has occurred in the pressure charging procedure. It has been found that it is not necessary to stop at any pressure between 1 and 100 atm. to establish air purity in the channel, as had been done. Also the rate of pressurization has been increased. A typical sequence is now:

| time (min.) | event |
|---|---|
| 0 | arc started, 1 atm. argon |
| 4 | check completed of air arc at 1 atm. |
| 4 | reduce air flow to a trace |
| 14 | vessel pressure at 100 atm. |
| 14 | increase air flow |
| 18 | pure air arc at 100 atm. |
| 18-24 | self-extinction or arc jumps out of the channel |
| 60 | restart |

The advance in the pressurization method is important because of the reduction in the running time of the apparatus, particularly in the amount of exposure to hot air, for a given amount of new data on the air properties.

## Summary

A stable, pure air arc has been operated successfully for the first time at pressures between 50 and 100 atm. The measurements of the total radiated power (via quartz windows) allow a tentative conclusion that the radiative power per unit volume of air plasma near 9000°K is rather insensitive to pressure changes between 30 and 90 atm. and is only a few percent of the electrical input power.

The spectral information shows that the O 844.7 nm line used below 30 atm. to determine the temperature profile should still be suitable at 100 atm. It is well isolated, and has an integrated intensity far above the intensity of the nearby continuum. It is easily resolved from two strong nearby argon lines at 840.8 and 842.4 nm. The presence or absence of the nearby argon lines minimizes the time invested in checking the purity of the arc column. The O 844.7 nm line at 100 atm. is broader than the line at 30 atm. and at 100 atm. is somewhat broader than the bandpass of the exit slits of the spectrometer. But this should not be a severe problem. The degree of opacity of the arc to radiation at 844.7 nm has not yet been established at 100 atm.

At present, after air purity is established at 100 atm., one has from 30 seconds to 3 minutes to take data before the arc extinguishes or jumps channel. There is little warning that this is about to occur since the arc maintains steady parametric average values. However, there are voltage spikes occuring in the channel which are quite sensitive to just how the arc is being manipulated.

A few minutes of data taking is sufficient to progress in the scientific knowledge of air plasmas at high pressures. However to increase the duty cycle, effort continues to be made to decrease the turn-around time between data runs, to speed up the data taking, and to find apparatus configurations and modes of operation which will increase the data-taking interval Experiments have started in a 4 mm. channel in order to try to reduce the frequency of the arc jumping from the channel, and arcs of higher current will be operated in the near future.

The plan is to spend about 50% of the effort taking data in the few minutes allowed and about 50% of the effort trying to expand the data-taking interval.

In the next month, the first attempt at operating at 150 atm. will be made.

References

1. "Transport Coefficients of Air at Temperatures of from 3000 to 25,000°K at Pressures of 0.1, 1, 10, and 100 atm.", I. A. Sokolova, AD-779-809, FTD-HT-23-907-74, National Technical Information Service, 5285 Port Royal Road, Springfield, Va., 22151.

2. "Electrical and Thermal Conductivity and Radiation Strength of Air Plasma at 1-30 atm. and 6,500-11,500°K", A. V. Larson and J. R. Williams, Final Report, Contract Number F40600-74-(C-007), Tullahoma, Tenn. 37389.

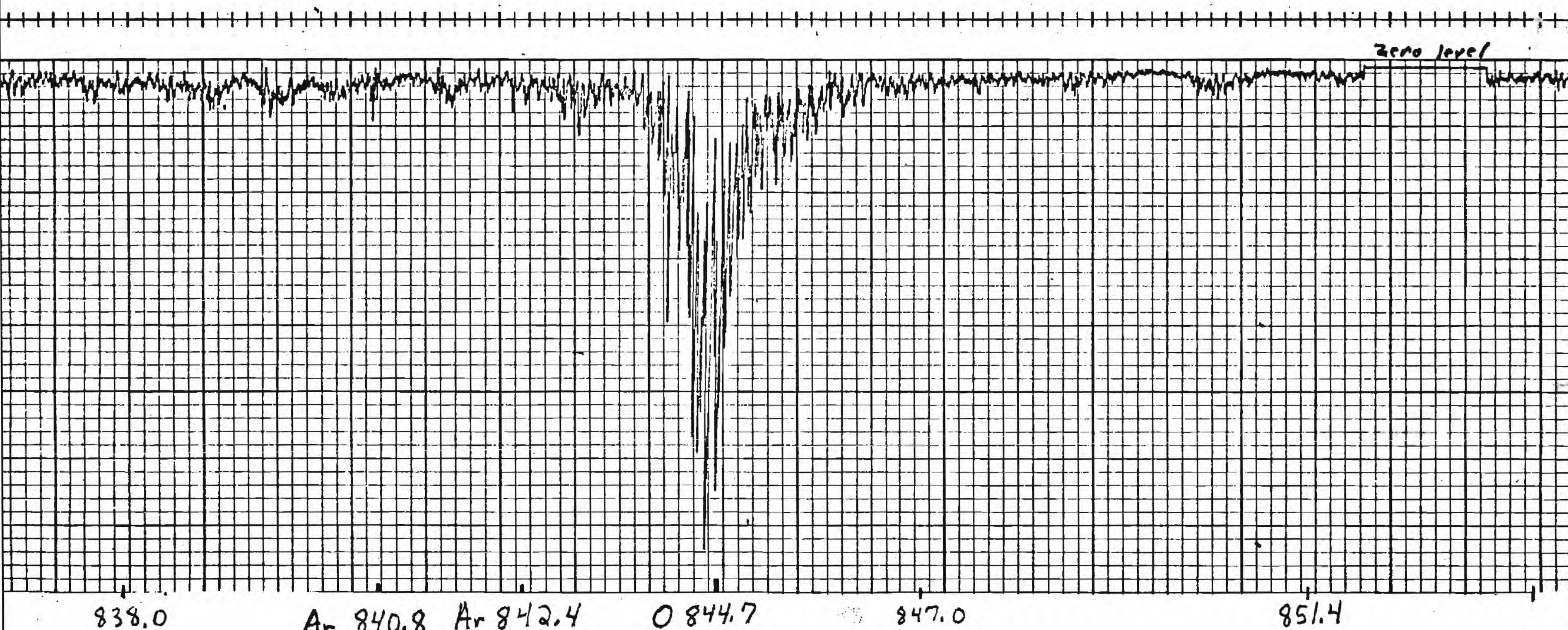



Fig. 1 Air Arc Spectrum at 100 atm.

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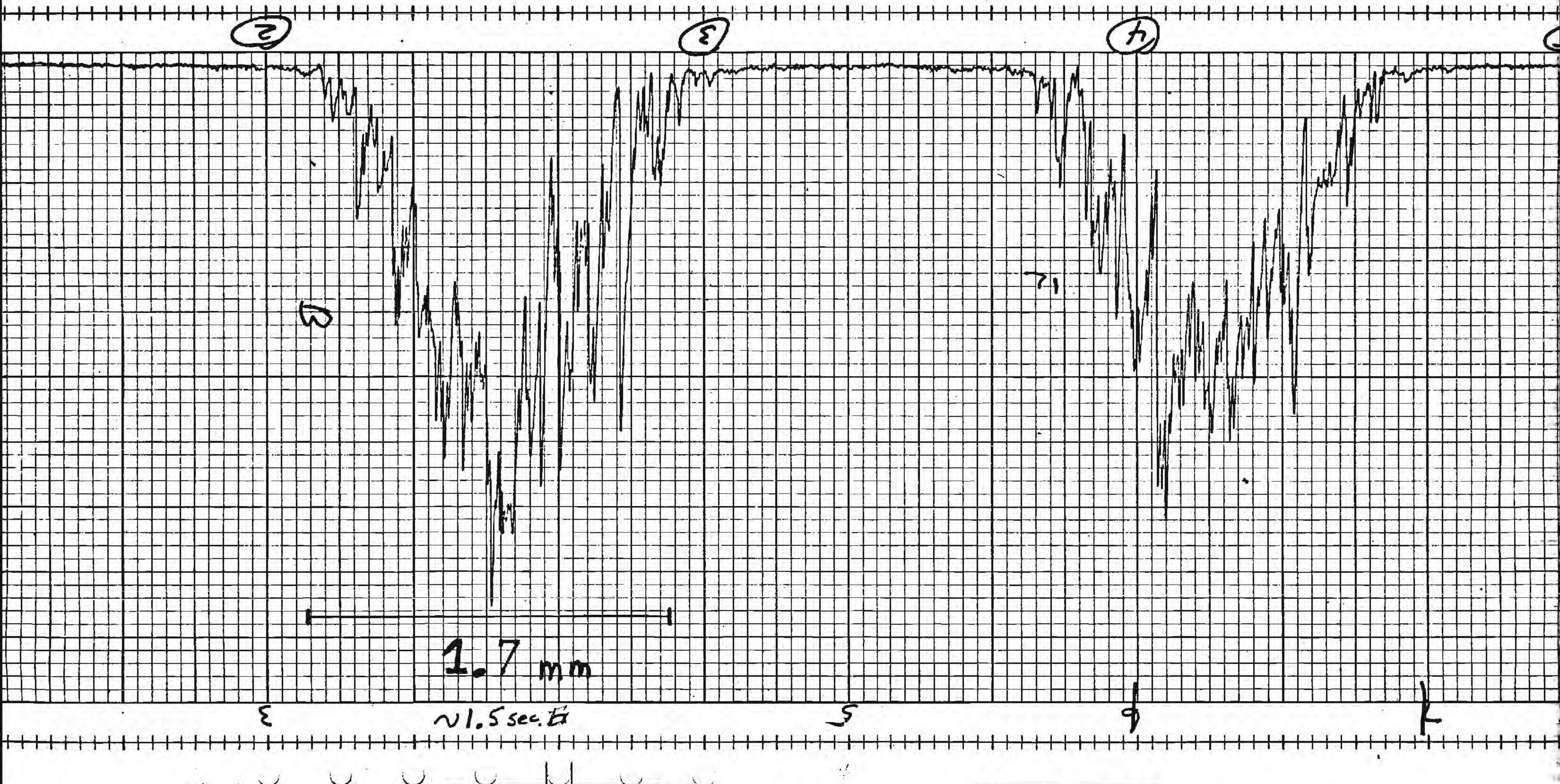


Fig. 2 Lateral Intensity Profiles of O 844.7nm at 100 atm.

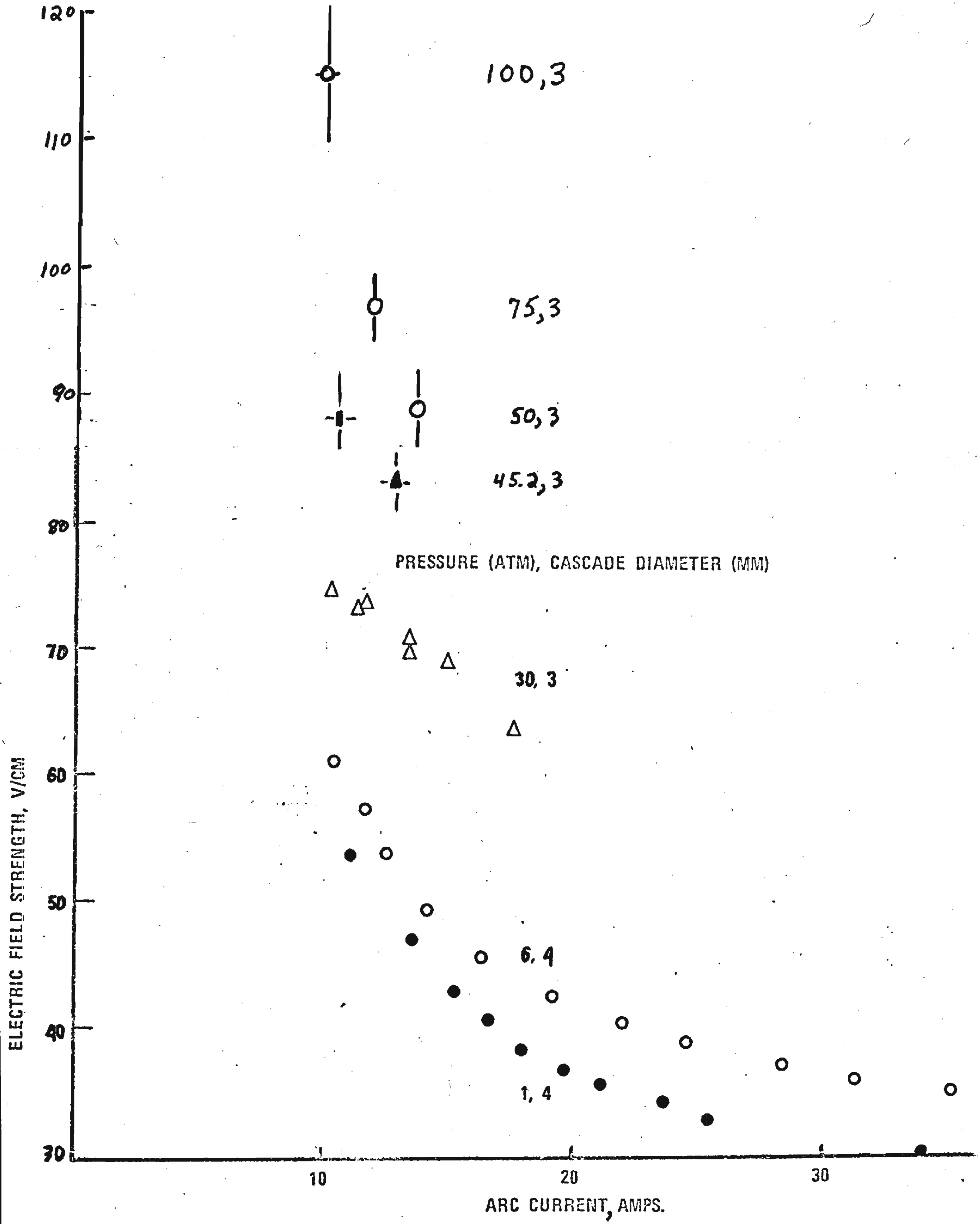


Figure 3. Arc Characteristics E (I, P) for Air.

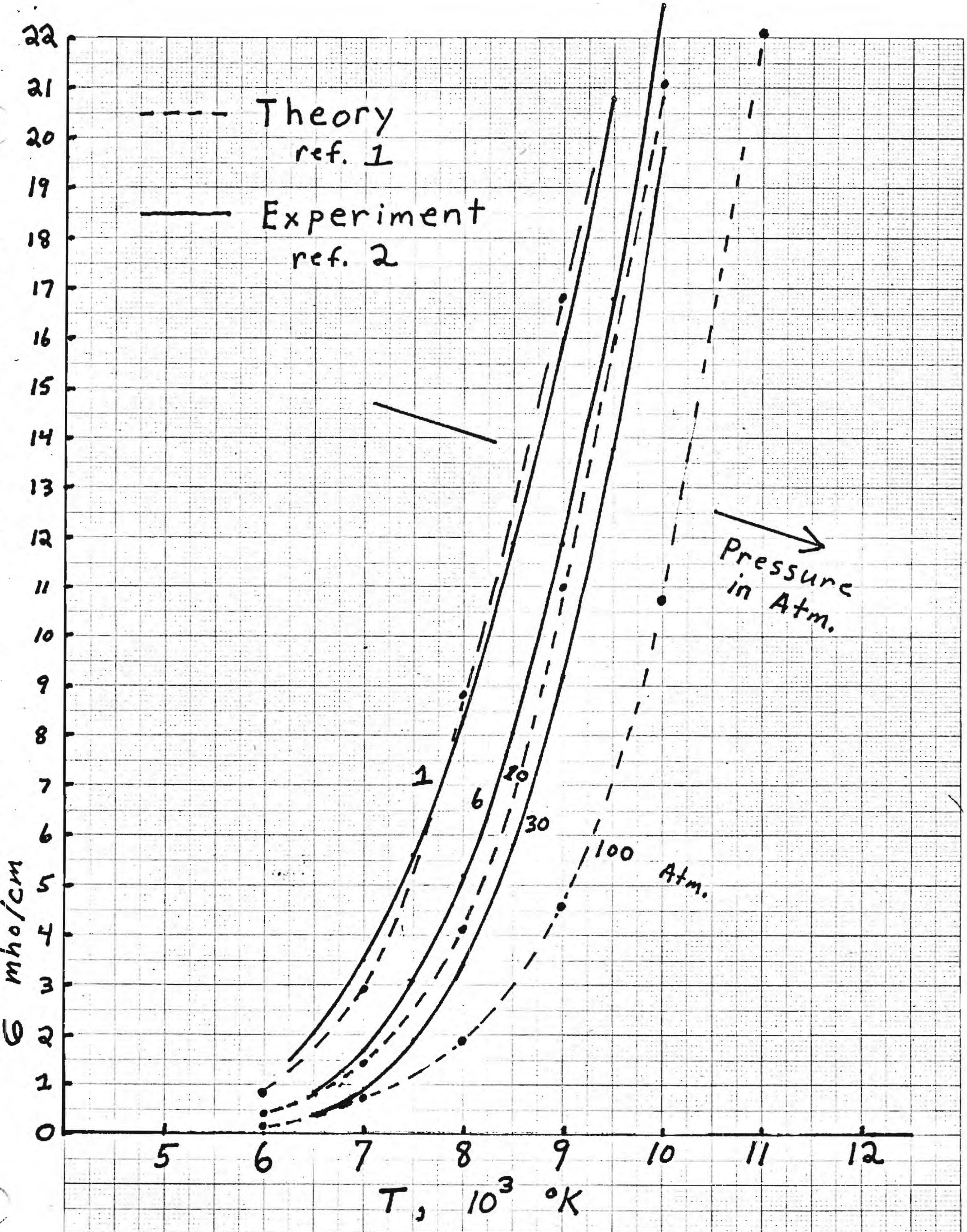


Fig. 4 Electrical Conductivity vs T, P

E-25-660

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Monthly Progress Report

# MEASUREMENT OF THE TRANSPORT PROPERTIES OF AIR AT HIGH TEMPERATURES AND PRESSURES

Contract No. F40600-76-(C-0004)

Covering the period
March/April 1976

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## Progress Report

Experiments on an air arc at pressures between 30 and 100 atm have been done using a larger bore diameter, 4 mm, and the results have been contrasted with data taken earlier using a 3 mm diameter. Also, some work has been done at currents both greater and less than previous currents. Additional comparisons of the experimental data with theoretical predictions for the data at 1, 6 and 30 atmospheres have been made.

As last reported, the experimental time at high pressures with the 3 mm bore has been limited to about 3 minutes by either the arc jumping out of the channel (and through the plates) or by a self-extinction of the arc. It has been found that the latter was due to a mismatch between the arc and the power supply whereby the supply could not provide enough voltage. The self-extinction problem has been eliminated by the series addition of an identical power supply module.

The problem of the arc transferring to the walls remained and provided the rationale for an increase in the bore diameter. The increase was intended to lower the electric field strength in the arc column and to lower the temperature (i.e. electrical conductivity) of the gas near the walls.

### Data

The arc characteristics of the 4 mm arc at pressures of 50 and 100 atm are plotted in Figure 1 along with previously reported data. The trend of electric field strength vs. pressure for an arc of 12 amp is given in Figure 2. As indicated, the field strength in a 4 mm air arc is about 10% lower than in a 3 mm arc.

The use of the 4 mm channel did not result in a noticeable suppression of the failure mode in which the arc jumps into the plates at pressures above 50 atm.

Nevertheless, it has been possible to make further measurements of the total radiation (via quartz windows) of the high pressure air arc. Figure 3 gives the radiated power per unit arc length vs. arc pressure and current. In Figure 4, the same data is expressed as a percentage of the electrical input power per unit length, IE. In Figures 3 and 4, all the data at pressures above 40 atm is new data, with the exception of the point at 93 atm which appears to be an anomaly (see also Figure 1). The new data represents more extensive support for the tentative conclusions drawn in the last report, namely that radiative losses at pressures between 30 and 100 atm are comparable for air plasma near 9000°K and are a few percent of the electrical input power.

It is to be noted that the first radiation data at 50 atm, which was reported in the Dec. 1975/Jan. 1976 report, is erroneous. It is now known that the optical slit system at that time was admitting unwanted radiation onto the thermopile from the breather ports at the channel ends in addition to the desired radiation from the central test section.

## Technology

A major advance has occurred in the experimental time logged on the air cascade arc apparatus operating at pressures above 30 atm. More than 30 hours have been logged on the present device which is double the previous best record and is to be contrasted to the usual times of 1 hour (12 months ago when experience on air arcs at 30 atm was first acquired) and 5-10 min. (18 months ago when the air arc was first tried at 1-6 atm). A number of factors have contributed to the technological advance, some of which have been reported. The new observations are:

1) At low arc currents, if the arc jumps out of the channel in the central test section, the operator may quickly restore the arc to proper conditions by shutting off the air supply and then by turning the air back on slowly. The restoration takes less than a minute.

2) A design for the cathode and the cathode argon-supply chamber has been found which has resulted in longer cathode life, better retention of cathode shape, and the elimination of problems between the cathode and the first cascade plate.

## Discussion of Experiments

Although several problems have been eliminated one by one, the project is still being hampered by the phenomena of the arc jumping from the channel in the air test section at pressures near 100 atm. The ends of the plasma column where some argon is present appear to remain in the channel and radiate intensely, but the central air section either disappears from view or is seen to be outside the channel.

If the transferral of the arc to the plates is caused by a relatively large electric field, then Figure 2 suggests that the problem may become worse at the higher pressures which are of interest to AEDC. On the other hand, as in other gases, E may not increase so rapidly at higher pressures, and secondly, the boundary conditions at the plates may be less favorable for the plate surfaces to become anodes and cathodes as they must if the arc is to jump out of the channel.

There is some mystery associated with the observation that it apparently takes very little argon in the test section to prevent the "air" arc from jumping channel or to bring the pure air arc back into the channel once it has jumped.

The main argument for trying the same apparatus at still higher pressures is just the uncertainty involved in extrapolating the results obtained so far.

At 100 atm one might try to reduce E by operating at higher currents. However, the new data in Figure 1, and other data not plotted suggest that above 50 atm, the air column is essentially a constant voltage, constant E device for currents between 5 and 25 amp.

Of course, there may be other causes for the arc to jump channel. For example, the material exposed to the plasma may be getting too hot. Using idealized cascade plate geometry, it has been estimated that the column could safely operate at 4000 watts/cm without damaging the copper. Most of the data in Figure 1 was taken at power levels between 1000 and 2000 watts/cm. Complicating matters, there are high-temperature rubber gas seals about 1 cm from the arc, the effect of which is unknown. Up to now, there has been no need to instrument for the purposes of measuring surface temperatures so such information is lacking.

Another possible cause for the arc to jump channel could well be the short duration excursions of the E field intensity away from the average value. On the oscilloscope, AC coupled, such transients appear as an abrupt increase followed by a declining ramp lasting about 10 msec before the next abrupt increase. The magnitude of the E-transients relative to the average E depends upon operating conditions as will be discussed later.

The E-transients in an air arc with argon ends were recognized in this project at the time of the first parametric survey of arc operating characteristics at a pressure of 6-7 atm (Ref. 1). It was noticed that a 4 mm arc operated steadily at low currents, but between 35 and 36 amp there was a sharp threshold for a turn-on of a very unstable arc condition with which was associated major E-transients. A theoretical paper (Ref. 2) was found which suggested that at low currents the plasma would be in a laminar condition which could accommodate the necessary conduction of thermal energy to the walls. As the electrical input power is increased to a critical value, the arc would first go into a standing helix, then into a turbulent mode in order to dissipate the energy to the walls. For some gases, one would expect a further increase in current to restabilize the arc due to the increasing importance of radiation losses. Using Ref. 2 as a guide the Georgia Tech air arc was run at 7 atm. and 115 amp and was found to be very stable. Again at 30 atm, it was found to be necessary to keep the current below 20 amp in order to achieve sufficient steadiness in the spectroscopic data (Ref. 3).

The experience at 30 atm was also in accord with Ref. 2 which predicts that the value of the critical current at which the instability is triggered decreases as the pressure is increased. There is no explicit prediction in Ref. 2 as to how restabilization at higher currents depends upon pressure. At the time of the work at 30 atm there was no need to pursue the subject further.

Although no work was done to establish the identity of the instability in the air arc, the predictions of Ref. 2 were in qualitative agreement with experience and so were used as guidelines at higher arc pressures. Figure 1 illustrates the initial choice to concentrate on the lower current arc at pressures above 30 atm but to keep I above 9 amp in order to limit E.

It is now known, as reported herein, that the air column with argon ends has relatively major E-transients in the pure air region when operated in the region above 50 atm which is shown in Figure 1. At the least, the presence of the E-transients reduces the usefulness of the spectroscopic data and at the worst may be responsible for the arc jumping out of the channel. Therefore, as this reporting period closed, attention was directed toward the E-transients.

Some pertinent accumulated experiences on pure argon arcs in this project were:

1) In pressurizing the 4 mm arc at currents near 15 amp, there exists a sharp threshold for the onset of major E-transients at 15 atm and they stay relatively large up to at least 100 atm.

2) In covering the parametric range of P, I in Figure 1 with a 2 mm argon arc, no note was made of any trouble with E-transients.

Another point from Ref. 2 is that at any pressure, the I-threshold for the initial onset of the helical instability increases as the bore diameter decreases. Thus items 1) and 2) above are in qualitative agreement with Ref.2.

A further observation related to item 1) is: If E-transients are present in the 4mm pure argon arc, then as air is introduced into the column center, the E-transients diminish and may even disappear (as definitely happens at 30 atm).

Finally it is found by experiment that a 4 mm air arc with 5 mm plates at the argon region adjacent to the cathode has considerably more instability than does a straight 4 mm channel.

Based upon the accumulated experience above, it may be hypothesized that:

a) A pure air arc may have a greater domain of stability than a pure argon arc,
b) The inherent instability of the argon ends may play a dominant role in upsetting the air test section,
c) The influence of the argon might be minimized by giving the end cascade plates a smaller bore.

## Discussion of Experiments in Progress

From the rationale just outlined, it was decided to make a new arc channel in which the bore at both argon ends would be smaller.

In the meantime, it is of interest to map out the stable regions of the present arc for the sake of comparative information. The data so far on the pure argon arc is given in Figure 5 and the data for the argon-air-argon column is in Figure 6. The stability refers to that of the central section of the column. The points that are connected by lines represent a continuous monitoring as an arc parameter is changed continuously. The dashed lines suggest boundaries between the stable and unstable regions.

Referring to the dashed line of Figure 5, it is found that if the arc is stable (low pressures) and the pressure is increased (I~15 amp), then the threshold is sharp and the onset of the instability is dramatic. The magnitude of the E-transients are suddenly comparable to the average E. On the other hand, if the arc is unstable (say at 10 amp, 21 atm), as the current is increased (at constant P), then the magnitude of the E-transients gradually lessen and disappear. In one experiment which started at ~12 amp, 100 atm, the E-transients were comparable in magnitude of the average E, i.e. the ratio was ~1. At higher currents (32,44,55 amp) the transients diminished and the ratios became (1/2, 1/3, much less) respectively, but it was not definitely established that the arc restabilized.

The restabilization of the arc at higher currents has been observed at 15, 21 and 23 atm for a pure argon arc and at 7 atm for an argon-air-argon arc. It is an important matter for the goals of this project to establish the boundary between the stable and unstable regions in air arcs.

Summary

Most of the experience in this project has been acquired with air arcs operating with the parameters mapped in Figure 1 with some additional work up to 100 amp at 1 and 6 atm. The plasma data sought in this project is to be found somewhere above the mapped region. However, it has been found to be difficult to operate an air arc with argon ends at the higher pressures.

At 100 atm the arc jumps out of the center test section within three minutes after air purity has been established there. It is speculated that the cause is either an excessive average electric field E, rather large E-field transients, or locally inadequate cooling. It not understood why a small amount of argon in the air will prevent or delay the jump or cause the "pure" air arc to return to the channel, especially since the presence of the small amount of argon has little effect upon any arc parameter except the line radiation spectrum which is used to detect its presence.

If the trouble is caused by an excessive average E field, the cure must be a redesign of the wall structure, perhaps with the inclusion of the new high temperature ceramics. One might also hope that at higher pressures or with different plate arrangements that the wall conditions would prevent the plate surfaces from acting as anodes and cathodes.

If the arc jumping is caused by the E-transients one can hope to eliminate them by operating the arc at higher and lower currents as suggested both by theory and other experiments. The bore diameter also has a strong influence in preventing or allowing the turbulence and inert gases other than argon might be more suitable for the end gases. Again ceramics might be useful in preventing the jump.

The E-transients have to be eliminated in any case for the sake of the meaningfulness of the data in this project.

If the arc jumping is suspected to be caused by locally inadequate heating, the apparatus will have to be instrumented for temperature measurements and appropriate fixes will have to be engineered.

With regard to the map in Figure 1, it is to be noted that to the right is a region of higher power. The present apparatus is limited to about 4000 watts/cm. To the left is a region in which E will surely climb and in which questions of thermodynamic equilibrium may arise. Finally at high pressures, E is fairly independent of I over most of the map and is increasing approximately linearly with P.

Thus there appears to be several ways around the present obstacles, but as usual, each way may have other difficulties.

This report of course is on the work at high pressure. However, some additional comparisons between theory (Ref.4) and the Georgia Tech work at

1, 6, and 30 atm. (Ref.3). Figure 7-A included in the last report, shows the comparisons of the electrical conductivity. Figure 7-B gives the theoretical prediction at higher temperatures. Figure 8 has the theoretical prediction of the coefficient of thermal conductivity for air plasma at 1, 10, 100 atm. In figure 9 the results of the Georgia Tech experiments are compared to the theoretical results. It is to be noted that Ref. 4 presents the theoretical results in tabular form at 1000 $^{O}$K intervals. The dashed lines of Figures 8 and 9 therefore are guessed lines which connect the tabulated data. Thus, neither the sharpness of the peaks nor the temperature at which the peaks occur are well specified. Finally it may be recalled that in Ref. 3 the experimental data was given a relative accuracy of $\pm$ 15% at the mid-temperatures of the experimental data range and a progressively larger error as either end of the range is approached.

References


1. Monthly Report, AEDC Contract No. F40600-74-(C-007), July 1974.

2. K. A. Ernst, J. Kopainsky, J. Mentel, "Helical Instability in Cylindrical Arcs", Eleventh International Conf. on Phenomena in Ionized Gases, Praque, Sep. 10 - 14, 1973.

3. "Electrical and Thermal Conductivity and Radiation Strength of Air Plasma at 1-30 atm. and 6,500-11,500°K", A.V. Larson and J.R. Williams, Final Report, Contract Number F40600-74-(C-007), Tullahoma, Tenn. 37389.

4. "Transport Coefficients of Air at Temperatures of from 3000 to 25,000°K at Pressures of 0.1, 1, 10, and 100 atm.", I.A. Sokolova, AD-779-809, FTD-HT-23-907-74, National Technical Information Service, 2585 Port Royal Road, Springfield, Va., 22151.

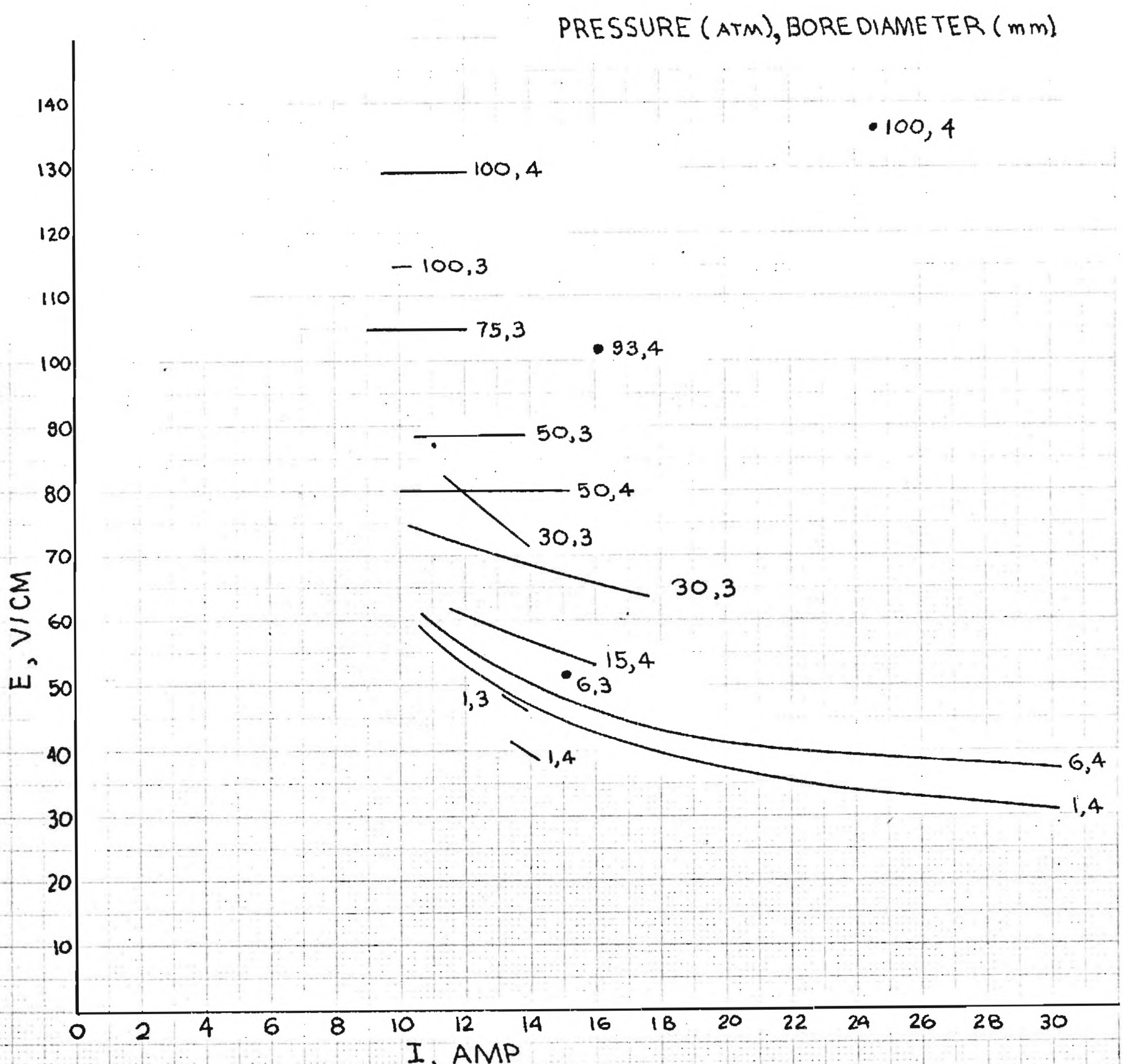



FIGURE 1: ELECTRIC FIELD STRENGTH vs CURRENT AND PRESSURE

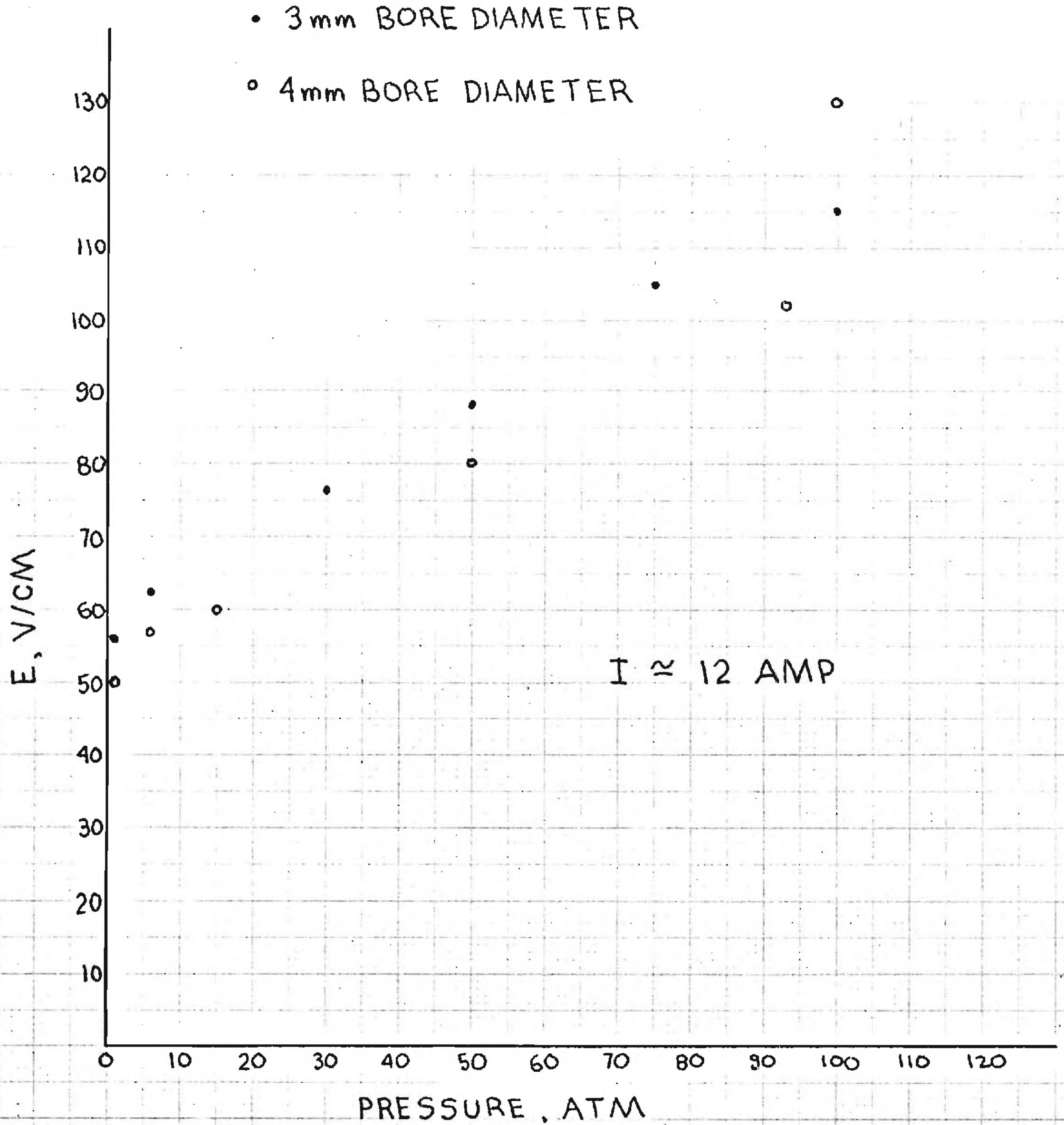



FIGURE 2: ELECTRIC FIELD STRENGTH vs. PRESSURE

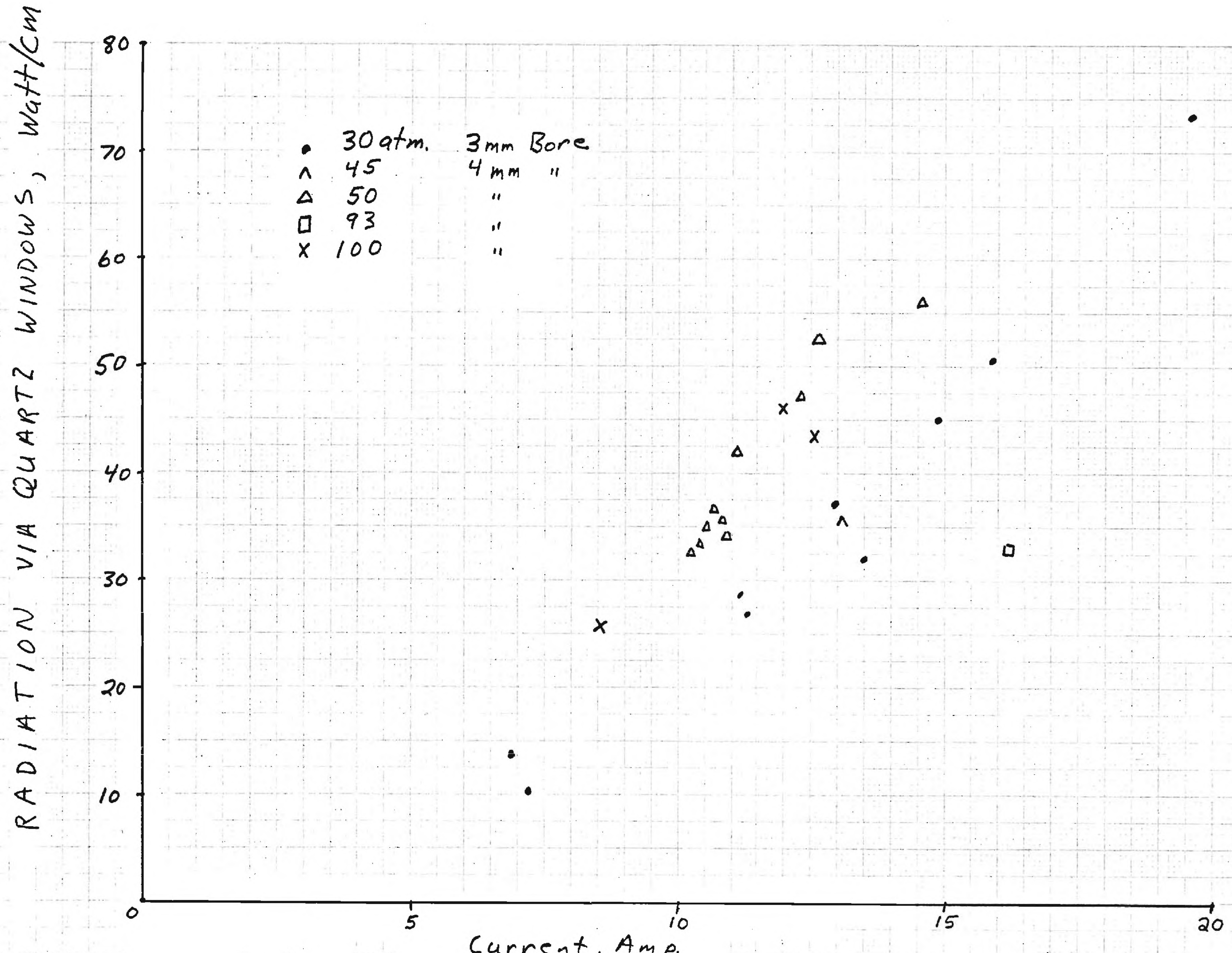



FIGURE 3: RADIATION / CM OF ARC LENGTH

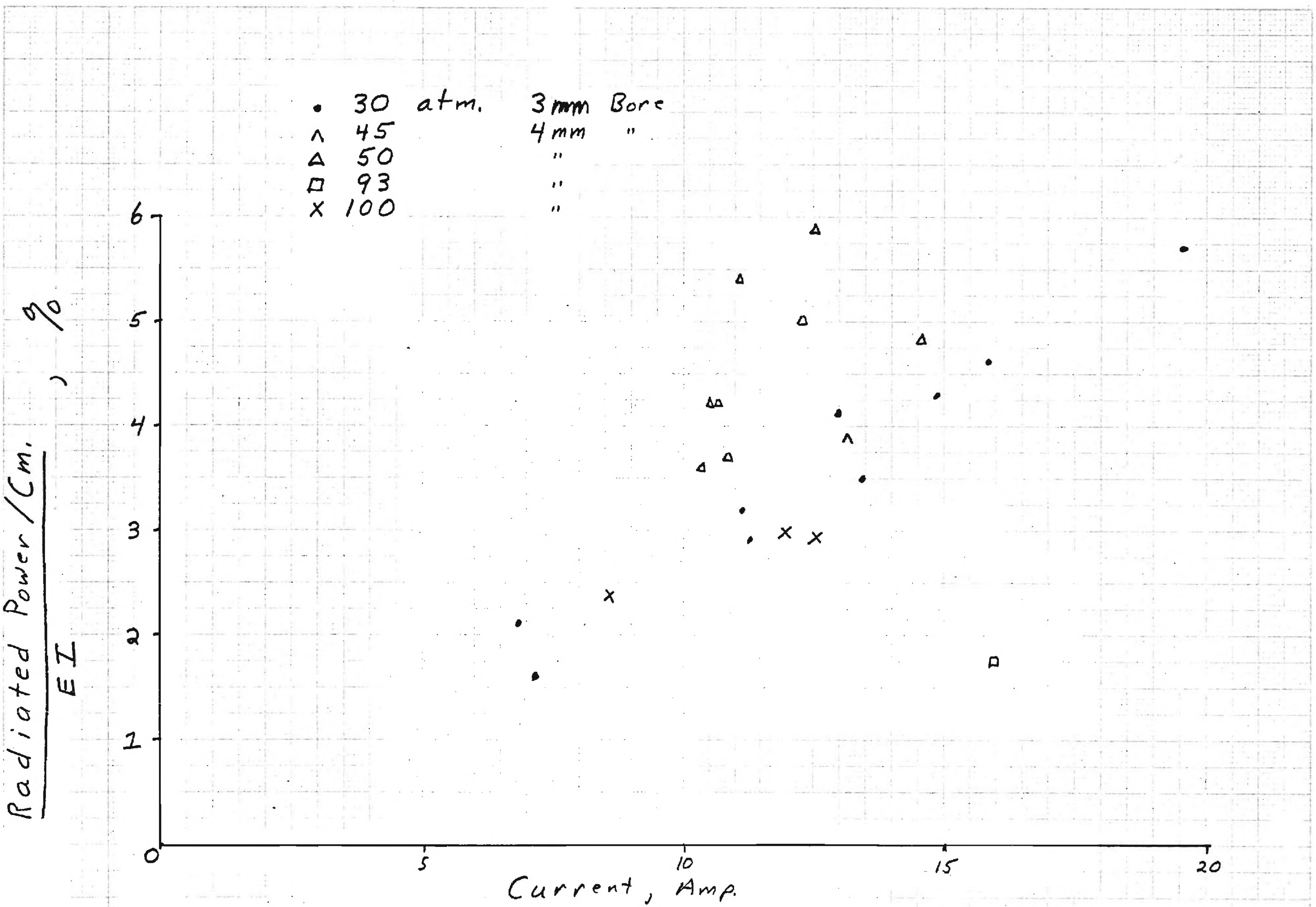



FIGURE 4: RADIATION LOSSES AS A % OF ELECTRICAL INPUT POWER

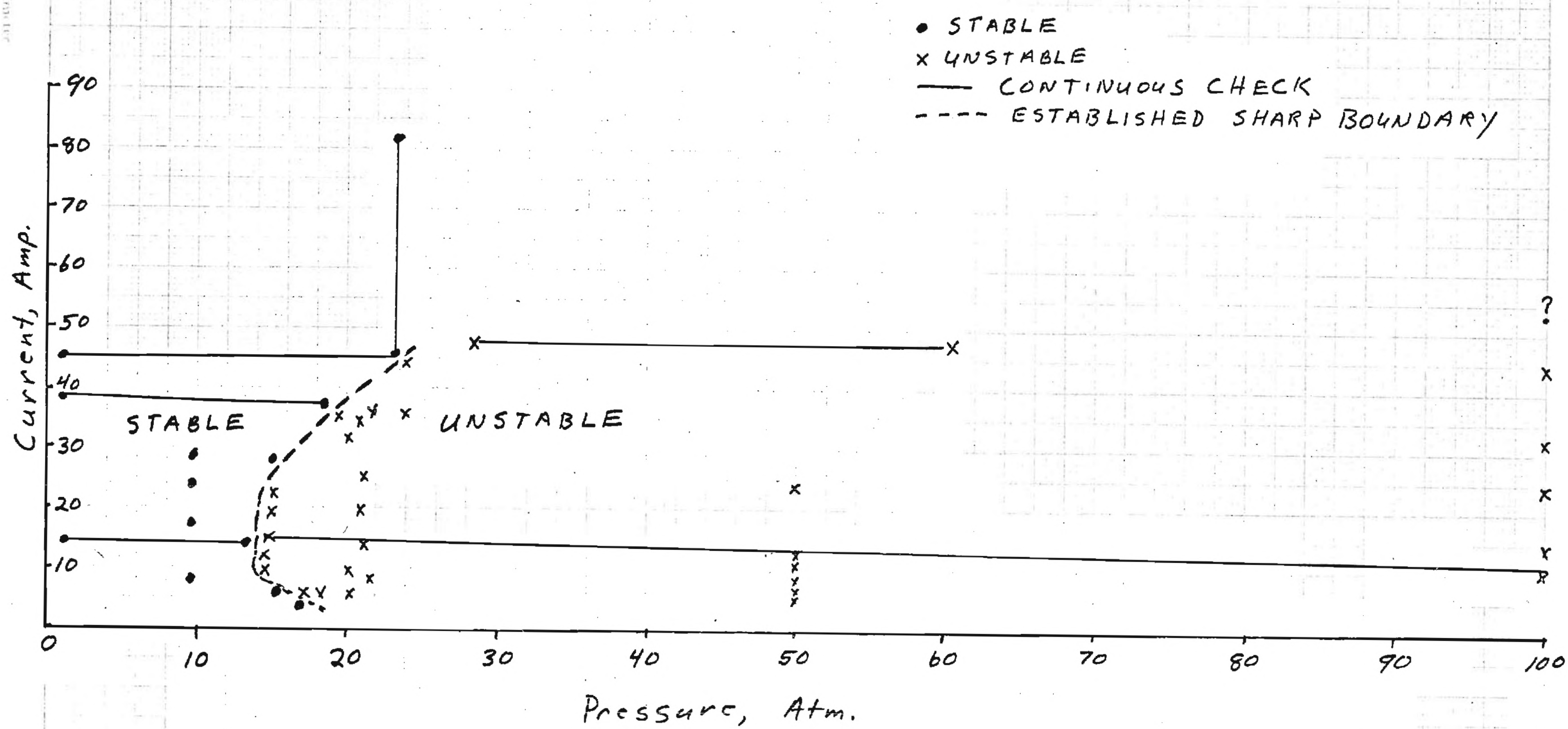



FIGURE 5: STABILITY OF 4mm ARGON ARC

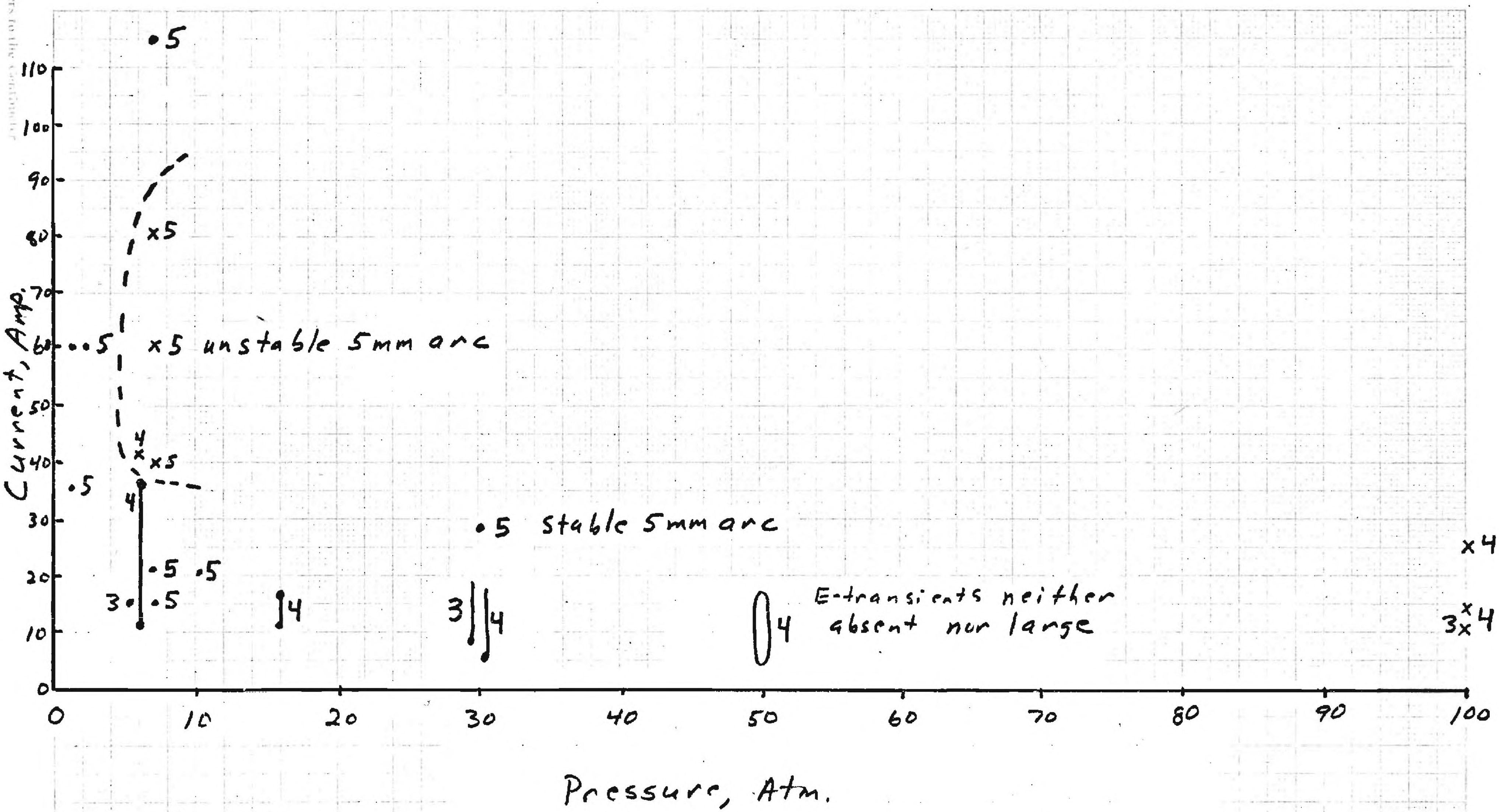


FIGURE 6: STABILITY OF AIR PLASMA COLUMNS WITH ARGON ENDS

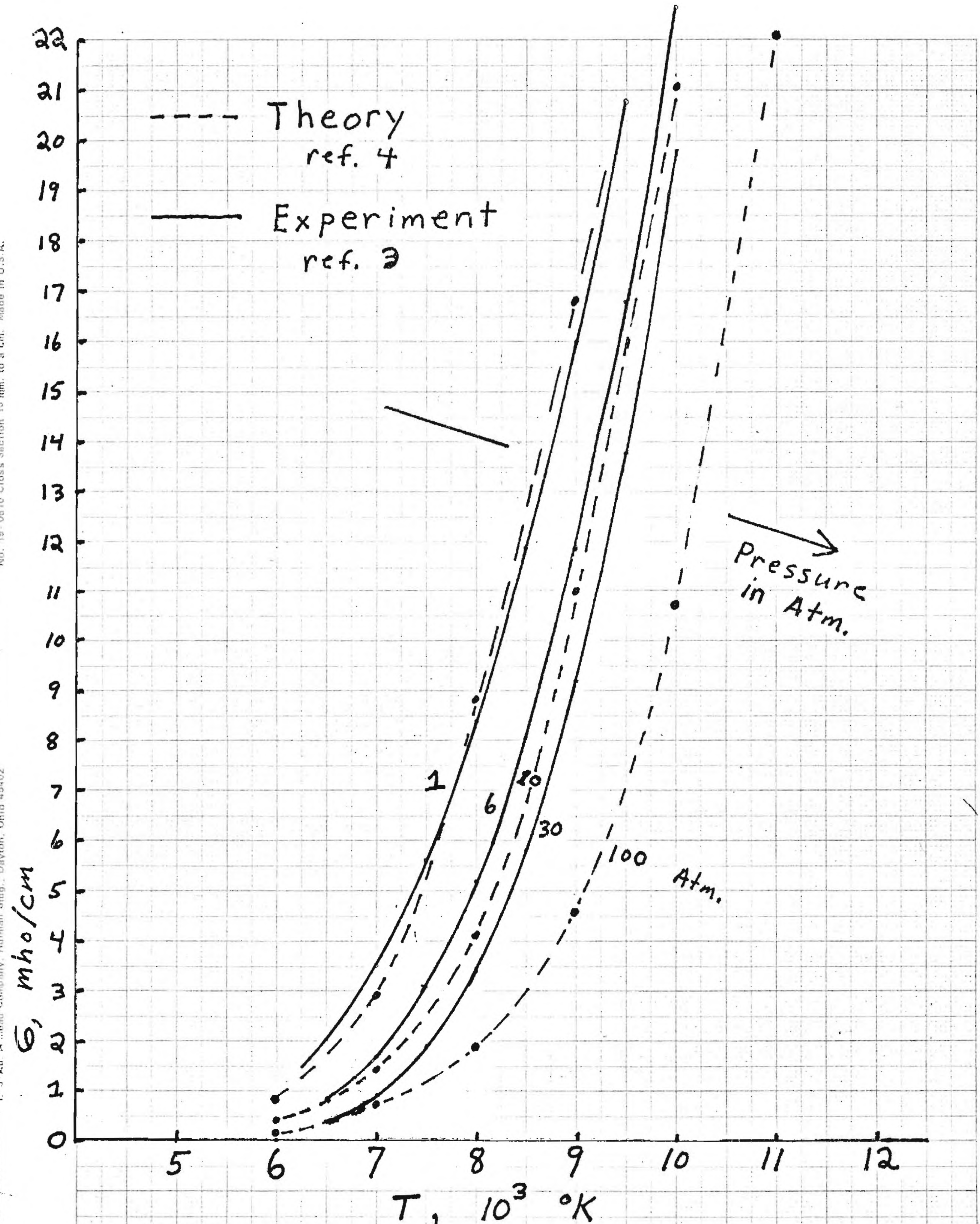



Fig. 7-A: Electrical Conductivity vs T, P

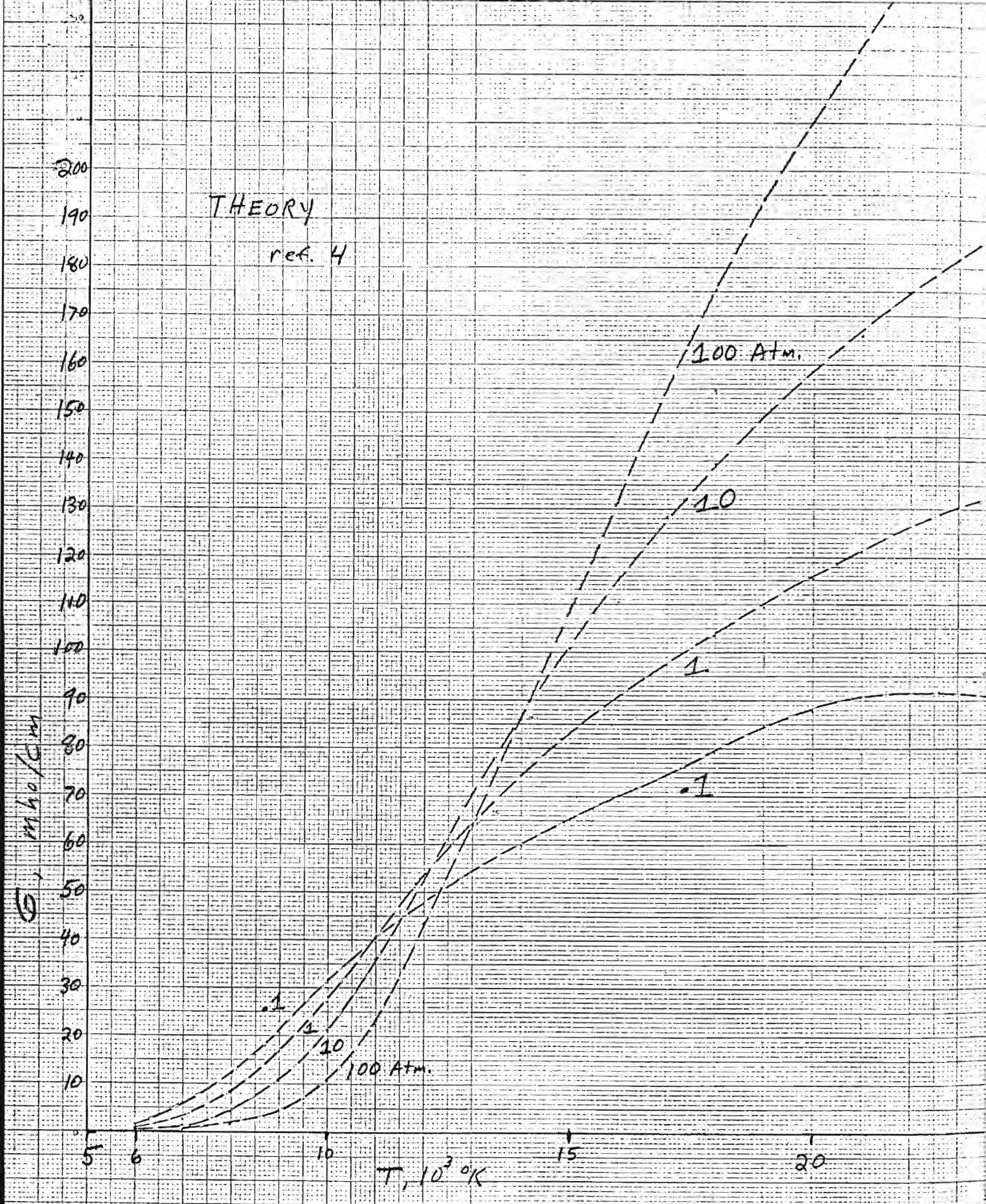



FIGURE 7-B: ELECTRICAL CONDUCTIVITY VS. T, P

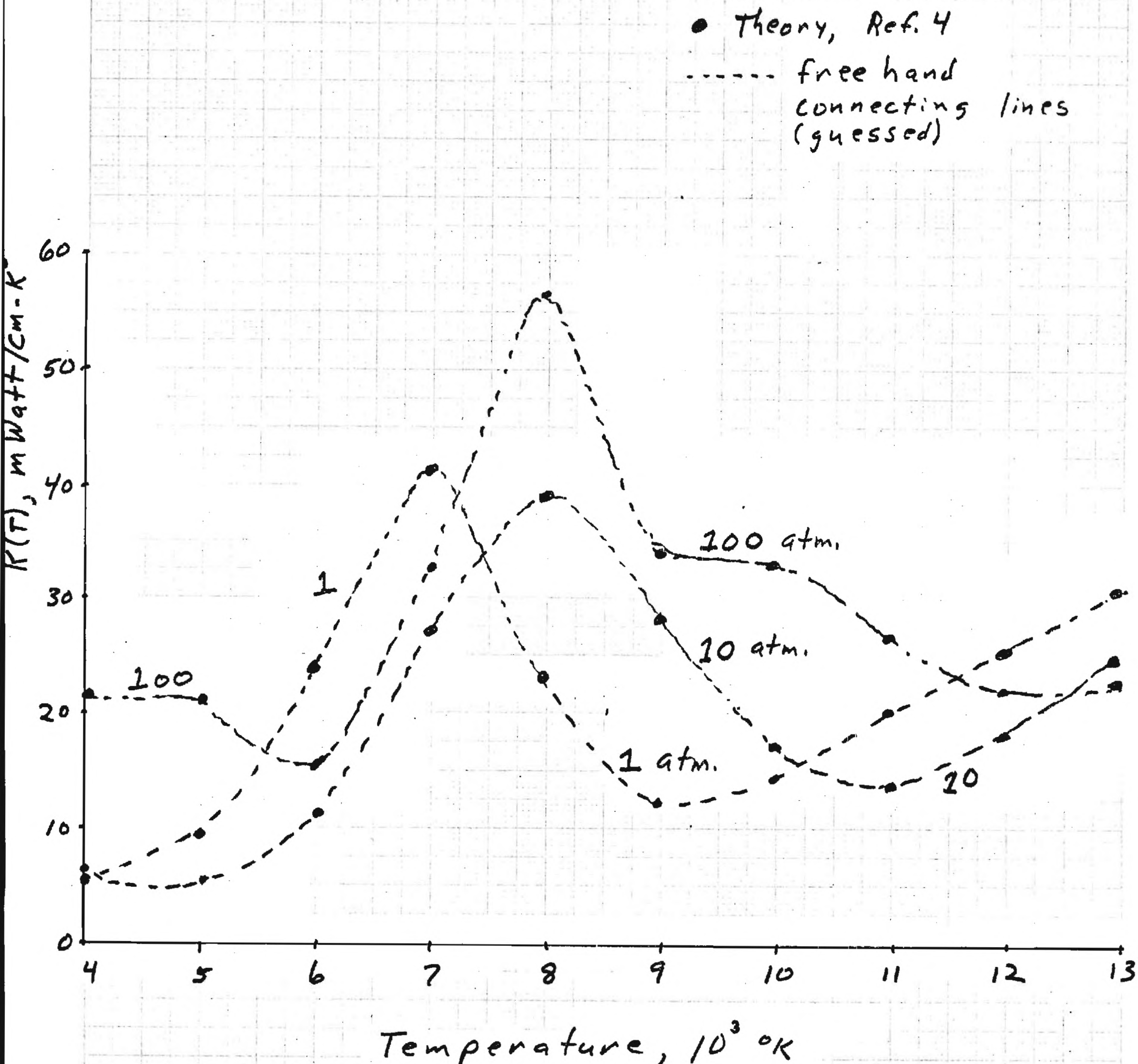



Figure 8: THERMAL CONDUCTIVITY OF AIR PLASMA vs. TEMPERATURE AND PRESSURE

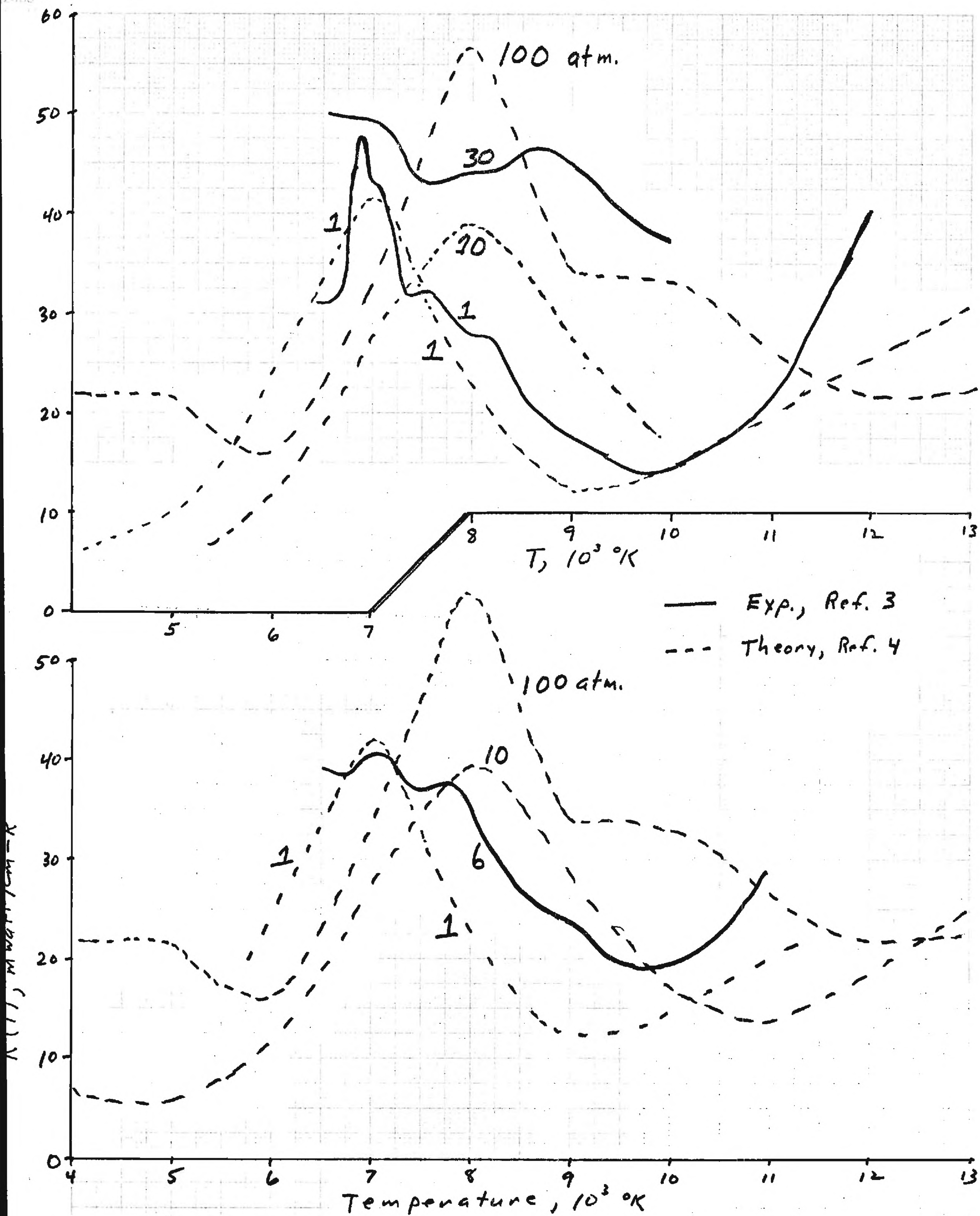



Figure 9 : Thermal Conductivity of Air Plasma

E-25-660

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Monthly Progress Report

# MEASUREMENT OF THE TRANSPORT PROPERTIES OF AIR AT HIGH TEMPERATURES AND PRESSURES

Contract No. F40600-76-(C-0004)

Covering the period
May 1976

Prepared by
A.V. Larson, R.T. Murray, Staff
J.A. Madill, D. Dodson, Students

Prepared for the

Arnold Engineering Development Center
Air Force Systems Command
Arnold Air Force Station, Tennessee

Progress Report

Work has continued on the wall-stabilized air arc with argon-protected electrodes. An advance in technology of such arcs operating at 100 atm. has occurred this month. Some experiments have now been done in which the central column did not jump out of the channel as air purity was obtained. The improved performance resulted from a number of changes in the construction of the apparatus. In a separate effort, a student paper has been completed which treats quantitatively one type of error in the deduction of electrical conductivity from measurements on electric arcs.

## Apparatus

The sketch shows a schematic of the apparatus at the time of the March/April progress report. The numbers on the sketch refer to changes made for the experiments reported herein.

As discussed last month, the arc at 100 atm. jumped channel shortly after air purity was established. It is difficult to blame this occurrence on a high average electric field strength, or on transients in the electric field, or on localized hot spots because, if a trace of argon impurity is present,the arc parameters are essentially the same, but the arc does not jump. Conversely, if a pure air arc has jumped channel, a slight argon impurity causes the arc to return.

The rationale for the present experiment came from the following hypothesis. Suppose that the indication of the trace of argon is significant, not in terms of the level of impurity, but instead in terms of whether the flow in the air column has been decoupled from the swirls that exist at the electrodes. Air is being injected radially in the test section and may have an induced, stabilizing swirl if the action at the breather ports does not decouple the flows. The absence of the argon spectral line in the test section may be a signal that decoupling is sufficient to remove the swirl, thus permitting a less stable arc to jump channel.

An air injection vortex had been used successfully in this apparatus at 30 atm. and below, but had been removed for other reasons at an early stage in the attempt to develop the 100 atm. operation. A vortex injector was reinstalled at point 1 in the sketch for the May experiments. The other three air feeder gaps were left in a radial injection configuration.

Other changes which were made and the reasoning behind them are given next.

It has been noted that the arc appears to be much more sensitive to changes in the flow patterns inside or outside the bore at the higher vessel pressures. Also after the record 36 hour experiment in April, deposits in the breather ports indicated that the breathers were not withdrawing gas symmetrically from the channel since the chamber vent consisted of only one pipe near the outside of the pressure vessel. In an effort to make the flow changes more gentle, the air distribution holes at points 2 have been reduced from .078" to .020". To make the breather action more symmetric, the single vent has been replaced by a ring vent at 3 which is axisymmetric with the arc.

The cascade plates are 2 mm. thick and are spaced about .25 mm. apart except at the test window and the breather ports which have greater gaps. The test window gap has been .5 mm. On the hypothesis that the window gap was too large for effective wall-stabilization, the gap at 4 was reduced to .25 mm. (A counter argument for increasing the gap to reduce the average electric field in the gap could be given.)

The bore of the plates at 5 and the anode at 6 was reduced to 4 mm. in an attempt to suppress the argon E-transients discussed in the last report.

A secondary vent to the inside of the pressure vesel (but not to the atmosphere), located at 7 somewhat higher than shown, was sealed off, and an argon vortex injector was added at symmetric positions 8. This combination was done in order to duplicate the successful operation at the cathode in terms of stability and minimal erosion. The argon injector at 9 was sealed then because of a lack of available gas lines.

In past development work, we have made one technological change at a time so that its effect might be isolated and identified. Now, faced with a major problem of the arc jumping channel at 100 atm. and aware of several hypothetical causes and the experimental time required to check them out individually, the decision was made to incorporate as many possible "cures" as was convenient.

The tenth change was in the operation. The pure argon arc was pressurized to 100 atm. before any air was admitted to the air plenums.

<u>Results</u>

The results of making the ten changes were mixed, but very encouraging. A well behaved air arc which showed no tendency to jump channel in region 4 was obtained for the first time at 100 atm. All portions of the arc were much less wobbly, and one had better control over the action at the breather ports. During the pressurization at constant current, 15 amp., the E-transient onset occurred at 45 atm. rather than 15 atm. (see April, Fig. 6). The delayed onset is probably due to the narrower bore at 5 and 6 (April, p.4). The procedure of pressurizing to 100 atm. before admitting the air worked successfully for the first time, i.e. a stable, pure air arc could be achieved with this fill mode.

There has been some concern about a possible schlieren effect due to gradients in the region 4-A. From time to time in other experiments at 100 atm., some waviness has been observed in the arc image, its presence being dependent upon operating conditions. In the latest run, where the window gap was halved, no waviness or wobble was visible to the eye.

While operating the stable, pure air arc at 100 atm., 14 amp., radiation measurements were begun. Total radiation was measured again, and the oxygen

844.6 nm. line was scanned several times at high resolution. The exit slit of the spectrometer was opened then to pass most of the line radiation, and it was found that even with the consequential poor resolution, it was possible to distinguish the O 844.6 line from the nearby strong Argon line (when a trace of Argon was present). The important point is that the spectrometer may be preset in the condition to measure the lateral intensity profile of the total line intensity and may be used in that condition to quickly check for purity. Thus valuable experimental time will not be consumed in the future by resetting the spectrometer.

The purity of the arc was lost when another argon bottle was switched in without minimizing the effects of the pressure impulse. Shortly thereafter, a plate in region 5 sprung a leak and the run was terminated.

Upon inspection the plates below region 5 were unmarked by the experiment, but the bore in region 5 was badly eroded. This may be due to letting the arc run too long after the leak was sprung, but it may also be due to the increased wall loading there. Recall that for these experiments, the anode region gas energy which would normally be swept up through port 7 is now going downward past 5 and "out" through the breathers. Secondly the channel bore is now a uniform 4 mm. bore and is not enlarged in regions 5 and 6.

Summary

The longest experimental run with a pure air arc has been achieved at 100 atm. The arc did not jump out of the channel for the first time, and there was no indication that it had any tendency to do so. The work proceeds upon the assumption that changes 1-4 were responsible for the improved performance and regions 5-9 may be altered further to improve their power handling capability.

As noted before (April, p.2) the cathode region continues to behave superbly. With an argon swirl injected at B, a cone shape and position have been found which have produced a trouble-free cathode region. The region below the lower breathers has been standardized and appears to act independently of the upper regions.

The new experiments give hope that the problems in the central regions have been solved. The hope now is that the upper regions can be returned to their previous successful condition without disturbing the central regions. The proof lies in future repeatability of the positive aspects of the recent runs.

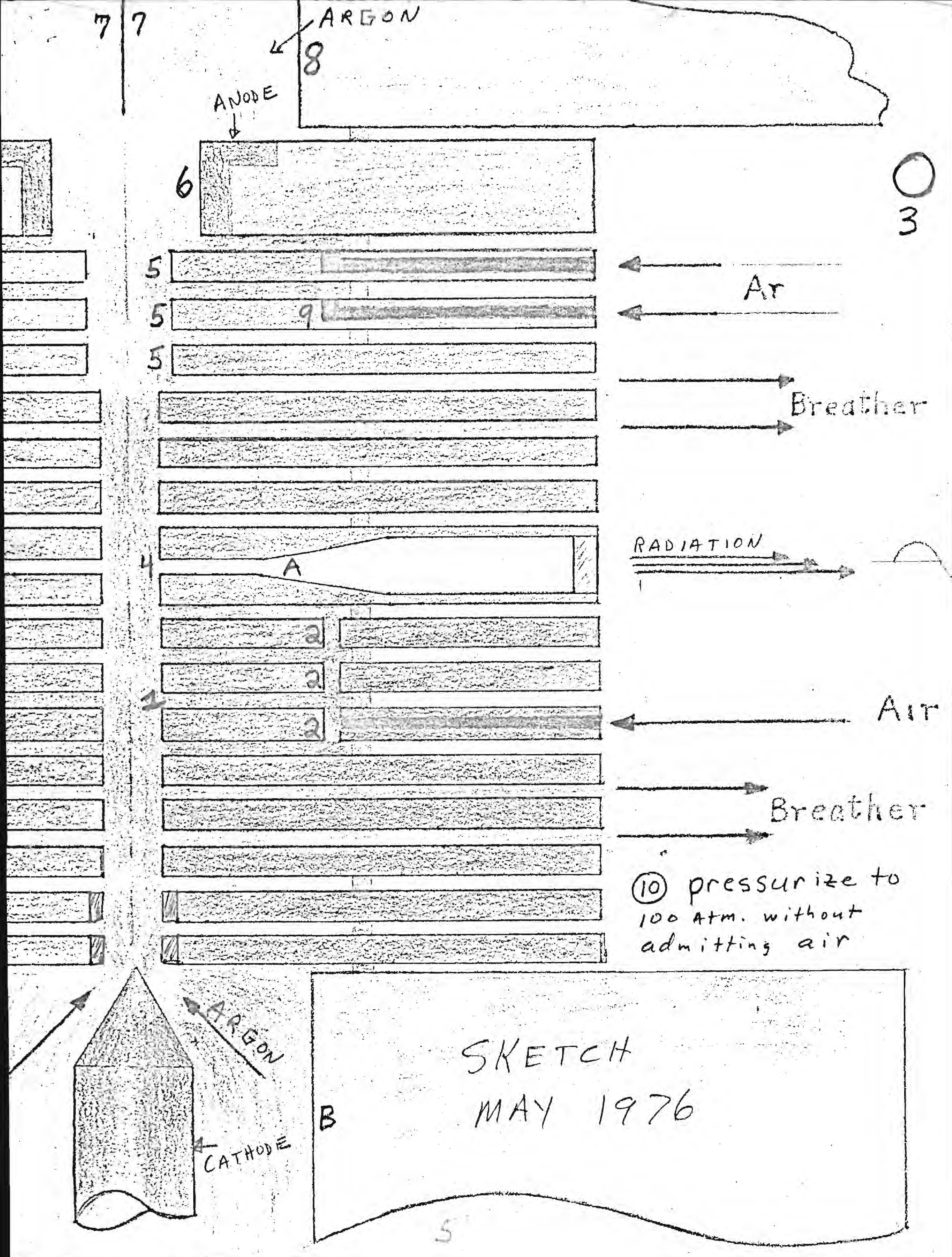
On the analytical side, a student paper by Daniel P. Dodson entitled, "An Analysis of Error in the Deduction of the Electrical Conductivity from Measurements on Electric Arcs" has been completed and is hereby made an appendage to this report. Mr. Dodson has made a quantitative study of the effect of the uncertainty in the temperature profile at the wall. The results indicate that no changes need be made in the error estimates of the final report of last year's effort due to that effect.

Enough data has been obtained from the altered apparatus to check against all previous 100 atm. data to see if the raw data has been affected by the changes in the sketch. Work is in progress on these comparisons. Furthermore, the advance in the spectral knowledge will conserve experimental time in future runs.

Mr. Tuwe Ohlson has joined the project for the Summer. Mr. Ohlson is an International Exchange Student from Chalmers University in Sweden. His contribution to the laboratory will be funded by non-project funds.

Dr. Larson gave paper IC7, "Electrical and Thermal Conductivity and Radiative Power of Air Plasma at High Pressures" at the 1976 IEEE International Conference on Plasma Science, Austin, Texas, May 24-26, 1976. The presentation was limited to the work at 30 atm. and below, for which previous clearance had been granted by AEDC. The audience suggested that the role of reabsorbed ultraviolet radiation be examined more closely, a point mentioned in the concluding remarks of the first report on the last contract.

Mr. R.W. Liebermann, Westinghouse Research Laboratories, Pittsburgh, has a general computer program which can generate theoretical curves of the kind shown in the April report, Figures 7-B and 8. He indicated a willingness to send Georgia Tech the results at 1, 6, 30 and 100 atm.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SKETCH
MAY 1976
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GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Monthly Progress Report

MEASUREMENT OF THE TRANSPORT PROPERTIES OF
AIR AT HIGH TEMPERATURES AND PRESSURES

Contract No. F40600-76-(C-0004)

Covering the period
June 1976

Prepared by
A.V. Larson, R.T. Murray, Staff
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T. Ohlson, IAESTA Student

Prepared for the

Arnold Engineering Development Center
Air Force Systems Command
Arnold Air Force Station, Tennessee

## Progress Report

New levels of pressure, current, power, electric field strength and apparatus life-time have been reached with the high pressure pure air arc column having argon protected electrodes. After months of frustation experienced in establishing a d.c. arc near 100 atm., a tough barrier has been broken, and the reward has been a delightful string of new operating records which, in counterbalance, have come quite easily.

### Experiments

In June, all down-times have been voluntary - there have been no failures of the apparatus. Several successful experiments have been done at pressures near 100 atm., one at 110 atm., one at 133 atm., and one at 143 atm. Lack of supply pressure prevented trying to operate at higher pressure as this report deadline arrived.

In each case the current and pressure were held steady, and the oxygen and argon spectral lines were used to determine purity. Then the O844.6nm line was chosen for a lateral intensity profile of the arc. The spectrometer exit slits were opened wide to accept as much of the line wings as possible. Approximately ten scans were achieved before changing the arc to a new operating condition. The total radiation as observed by a broadband thermopile was also recorded during the runs.

An example of a lateral intensity scan is given in Figure 1. The operating pressure and current were 143 atm. and 12 amp. The electric field strength in the plasma column was about 175 volts/cm on the average with transient excursions of about ±10%. It is believed that the noise on the signal is due to the E-transients and to an arc wobble. Both have been reduced in magnitude lately and there is a good chance for further reduction.

However, given 10 or more scans taken under identical conditions, statistical averaging should render the data suitable for further analysis. Toward this end, the scan signal is digitized and stored on magnetic tape.

As an example of the averaging process, consider Figure 2. In each row, a portion of a scan record is digitized at 1000 points. Each scan is digitized at about 300 points. The top record in the figure is the raw signal taken while running the arc in a less noisy (lower pressure) condition than in Figure 1. In the middle record, each point has been replaced by a three-point average. In the lowest record, each point is replaced by a five-point average. Continuing in Figure 3, the top record is a seven-point average, the next is a nine-point average, and the lowest is an eleven-point average.

Returning to the high pressure arc, Figure 4 shows successive scans at 100 atm., 8.5 amp. while Figure 5 shows the eleven-point average of the scans in Figure 4. Likewise for the two lower records in Figures 6 and 7. The top record in Figures 6 and 7 is for an arc at 100 atm., 13.6 amp. and was not recorded on an optimum scale. The top record in Figures 8 and 9 is for an arc at 110 atm. and 21 amp. Again a better scale should have been chosen. The two lower records in Figures 8 and 9 are for the tungsten ribbon calibration lamp recorded at different recorder gains.

It should be noted here that the major effort of the last few months has been devoted to getting the apparatus to work at 100 atm. For the data of this report little effort was extended toward minimizing the instrumentation noise.

In picking out scans with which to proceed, one looks for those which have the most symmetry and the least fluctuation, such as the lower left scan in Figure 5. One must discard scans like the right scan in the middle of Figure 5 which show an excessive temporary instability.

## Apparatus

The first real success at 100 atm. was outlined in the May report and came about as the result of 10 changes made in the apparatus. The 10 changes are numbered in Figure 10 and are discussed in the May report. The success was that the arc could be operated at 100 atm. without jumping the channel. However, it was found that the thermal load in region 5 was excessive. At that time regions 5 and 6 had the same diameter, 4mm., as the rest of the channel.

In early June, changes 5 to 10 were cancelled and the new success was achieved. (Cancelling 5 and 6 meant the anode region was returned to a 5mm and 5+mm diameter, respectively). In late June, the channel was returned to a straight four mm. channel, and success was achieved above 100 atm.

## Stability of the Arc

When the anode region is enlarged (5mm) the onset of the E-transients occurs at about 15 atm. if the arc is being pressurized at 15 amp. (March report, Figure 5). If the anode region is the same size as the channel, the onset occurs near 45 atm. In May and June the anode region was changed from 5 to 4 to 5 to 4mm. in successive designs and the observation on stability was repeatable.

In June, a plate near the cathode was removed and inserted above the window plates in an effort to decouple the anode region further from the test window. With this change, the cathode region was less stable, so the change was cancelled.

## Concluding Remarks

The major result has been the repeatable successful operation of the d.c. air arc in the pressure range from 100 to 143 atm. Therefore, the upper pressure limit for successful operation has still not been determined.

The many previous failures at 100 atm. due to the arc jumping channel in the test section were not due exclusively to an high E-field, for that parameter has risen from (120 v/cm at 100 atm) to (145 v/cm at 133 atm) to (175 v/cm at 143 atm) for a 12 amp. arc. See Figure 2 in the April report.

Nor were the failures due to a local hot-spot for the arc is now running consistently at higher power levels.

Now that the major technological problems have been solved for the 100-143 atm. arc, work can proceed on the credibility of the measurements necessary for the deduction of the transport properties.

The arc at 100 atm. has been run at enough different currents over the range from 8 to 21 amp. to allow the deduction of the electrical conductivity provided that the statistical averaging of the lateral intensity profiles at each current is meaningful. It would be especially interesting to proceed along these lines for there are available theoretical predictions at 100 atm. (Figures 7A,B, April report)

The noise problem should be tackled as a way to reduce the need for statistical averaging and to increase the accuracy of the averaging. It is thought that the noise is primarily due to the E-transients and the arc wobble. Both of these decrease as the channel bore is decreased. As was shown in Figure 2 of the March/April report, if the bore is returned to 3mm, the average E-field might be expected to increase by 10%. As has now been shown, such an increase may not prohibit successful operation.

In summary, the work can proceed further now in three important avenues: 1) Technological effort to extend the upper pressure limit past 143 atm. and toward the AEDC goal of 250 atm.; 2) Scientific effort to establish the credibility of the measurements at 100 atm. where theoretical predictions exist; 3) Scientific effort to establish the credibility of the measurements at 150 atm.

The work statement of the present contract is limited to item 3).

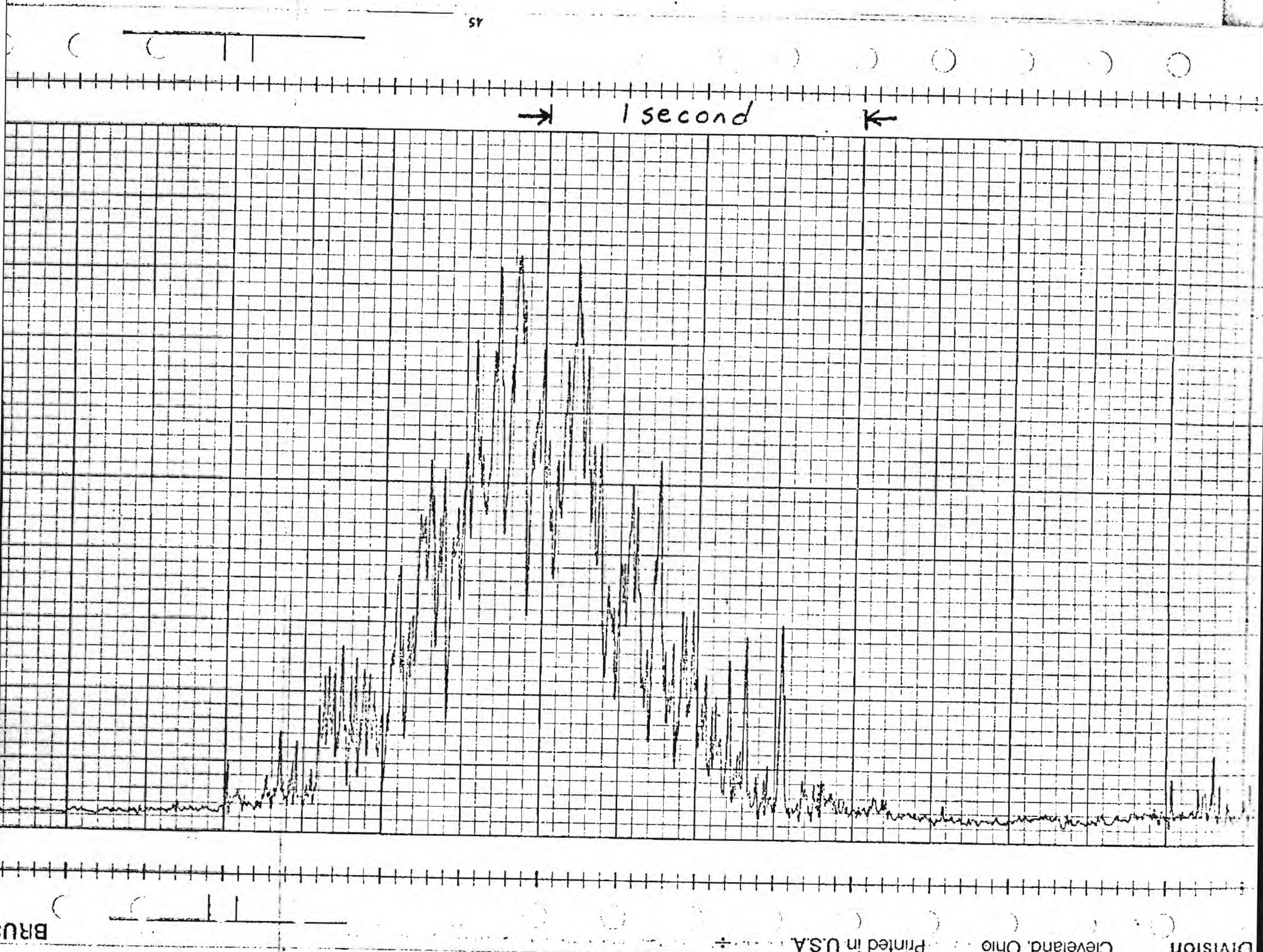


Figure 1: Lateral Intensity Profile of the 0844.6 nm line at 143 atm. and 12 amp.

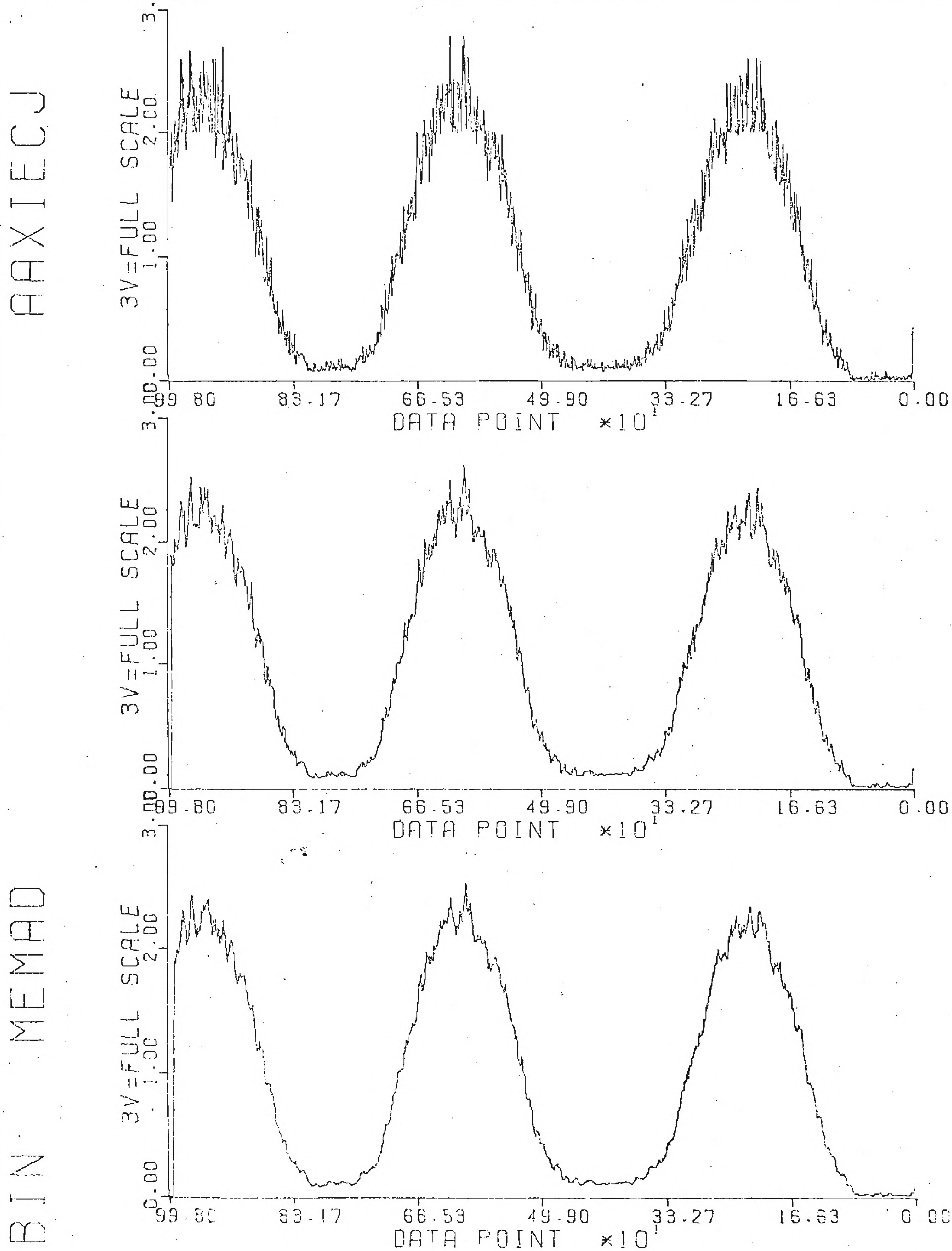

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Figure 2

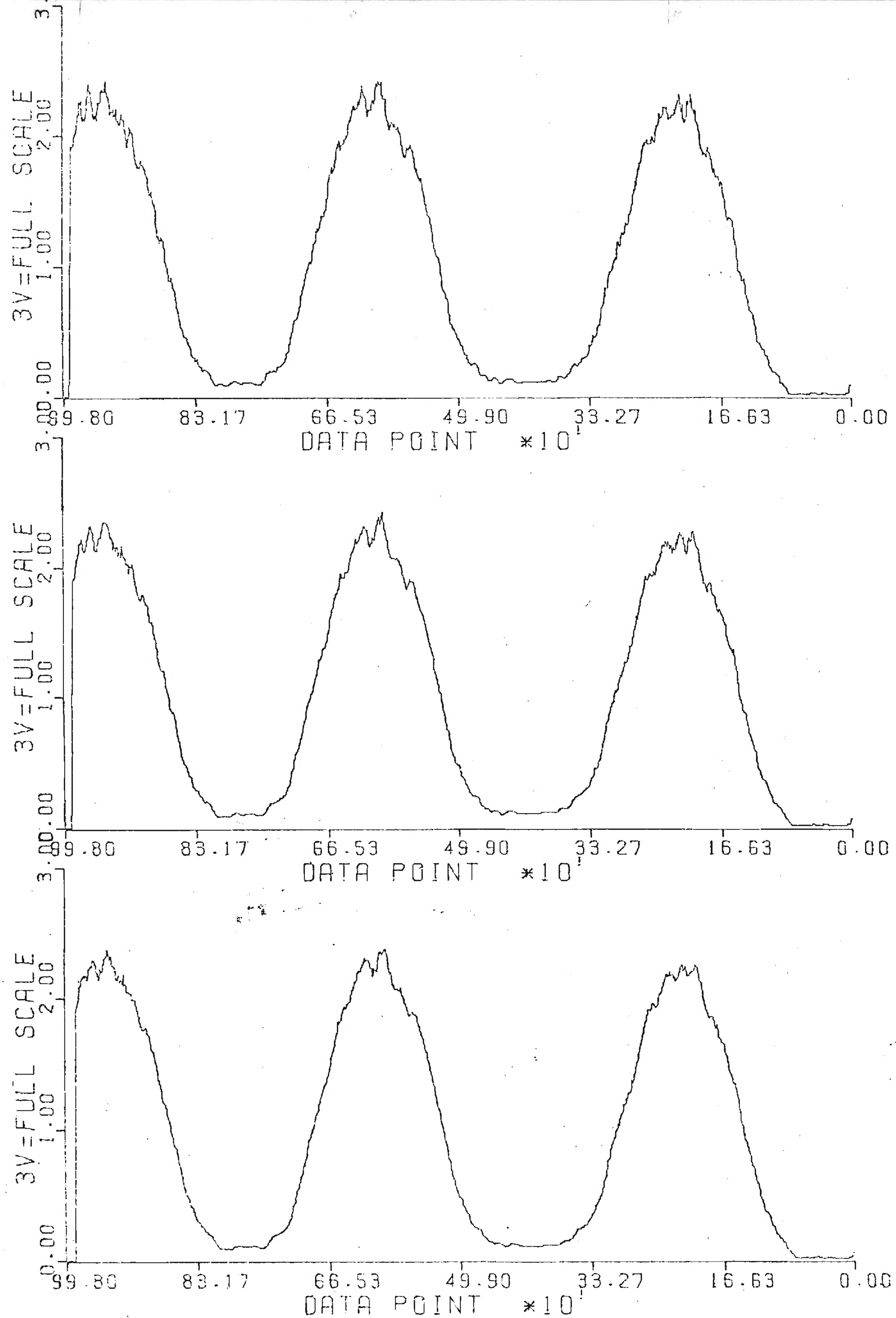
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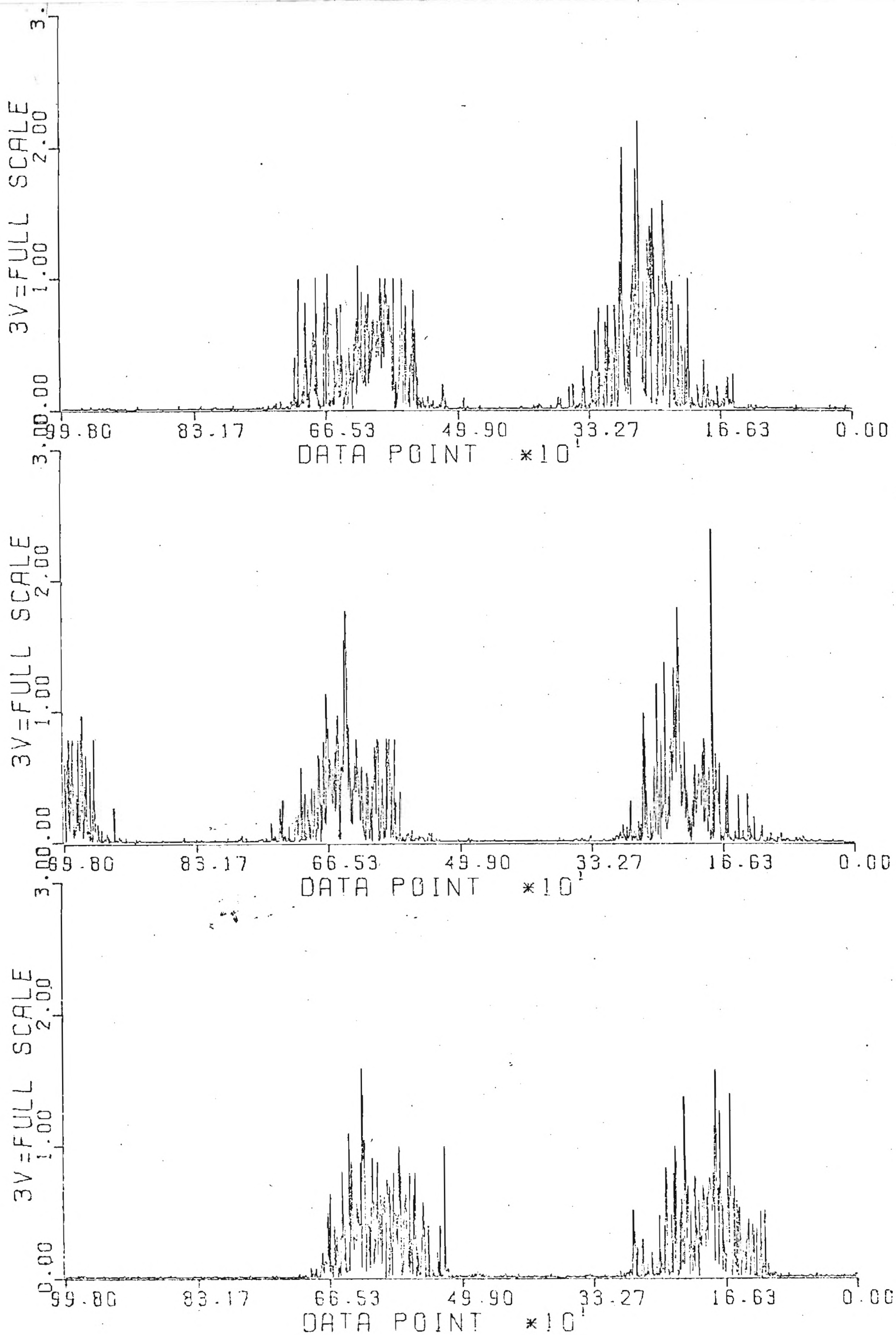
Figure 3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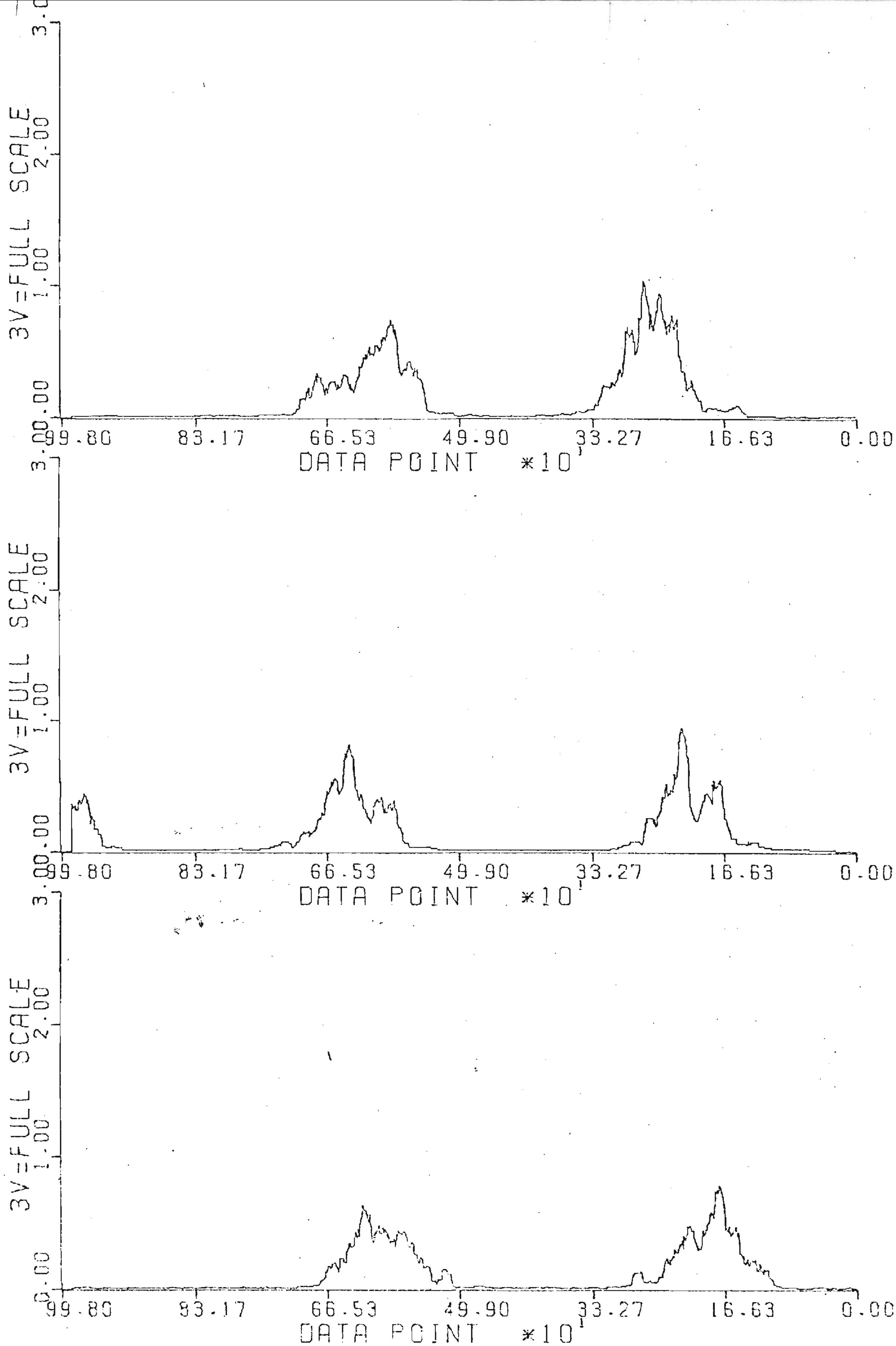
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Figure 5

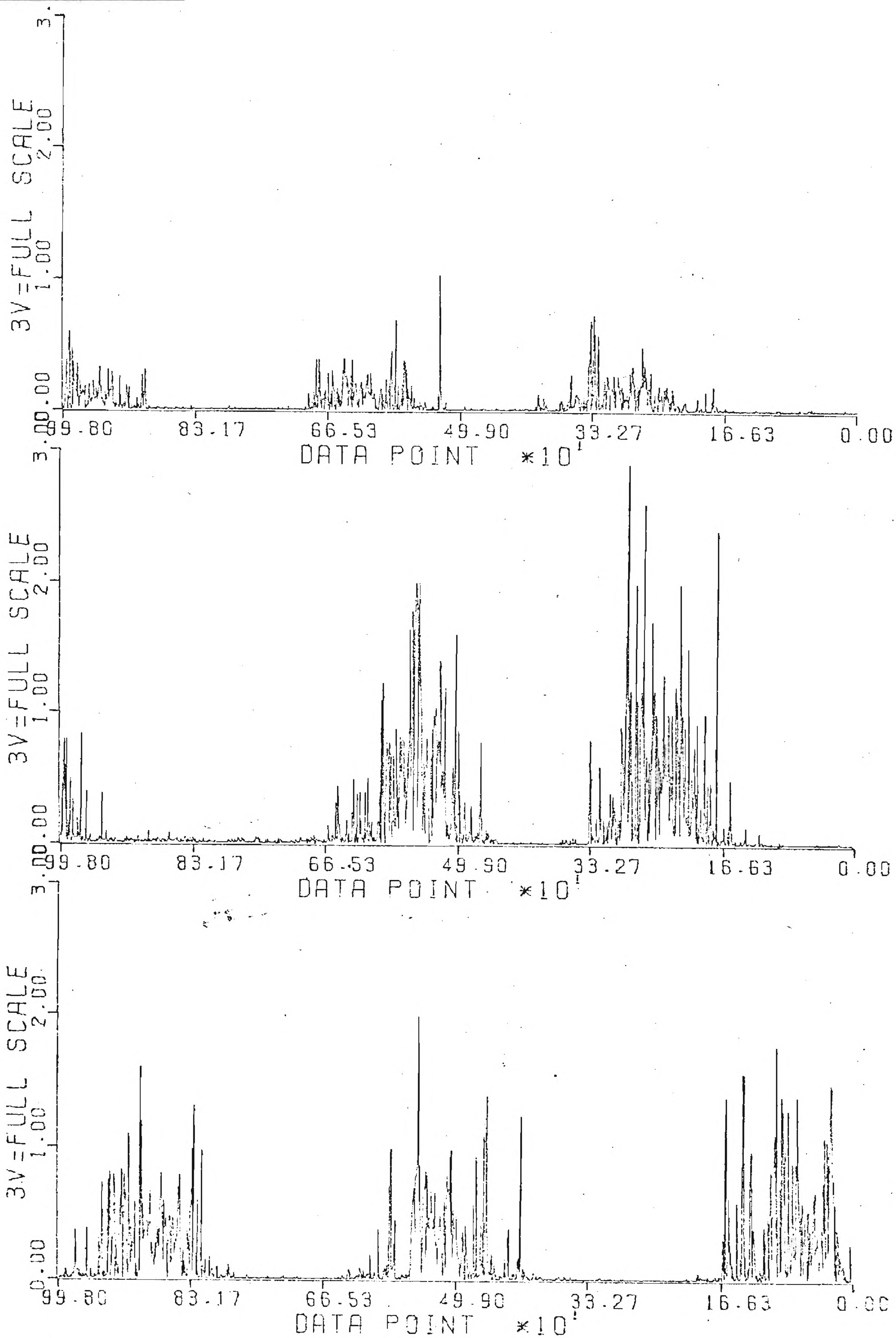
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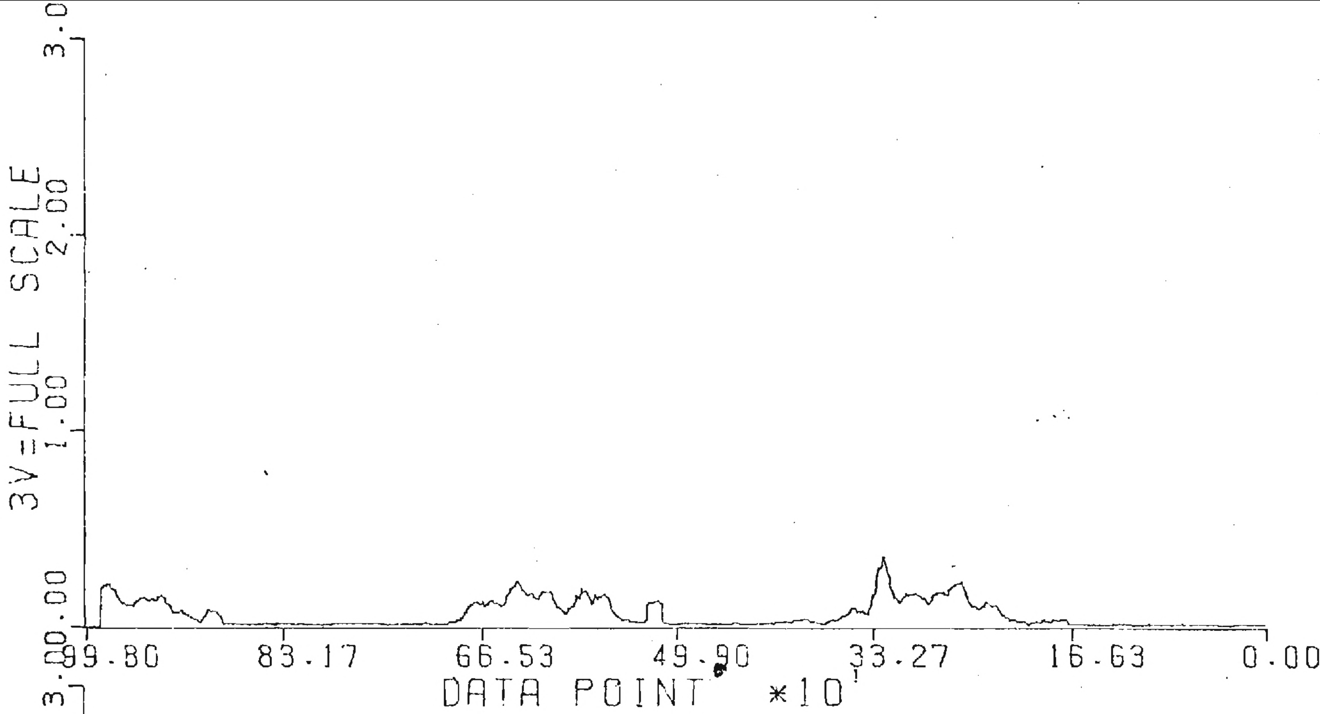
Figure 6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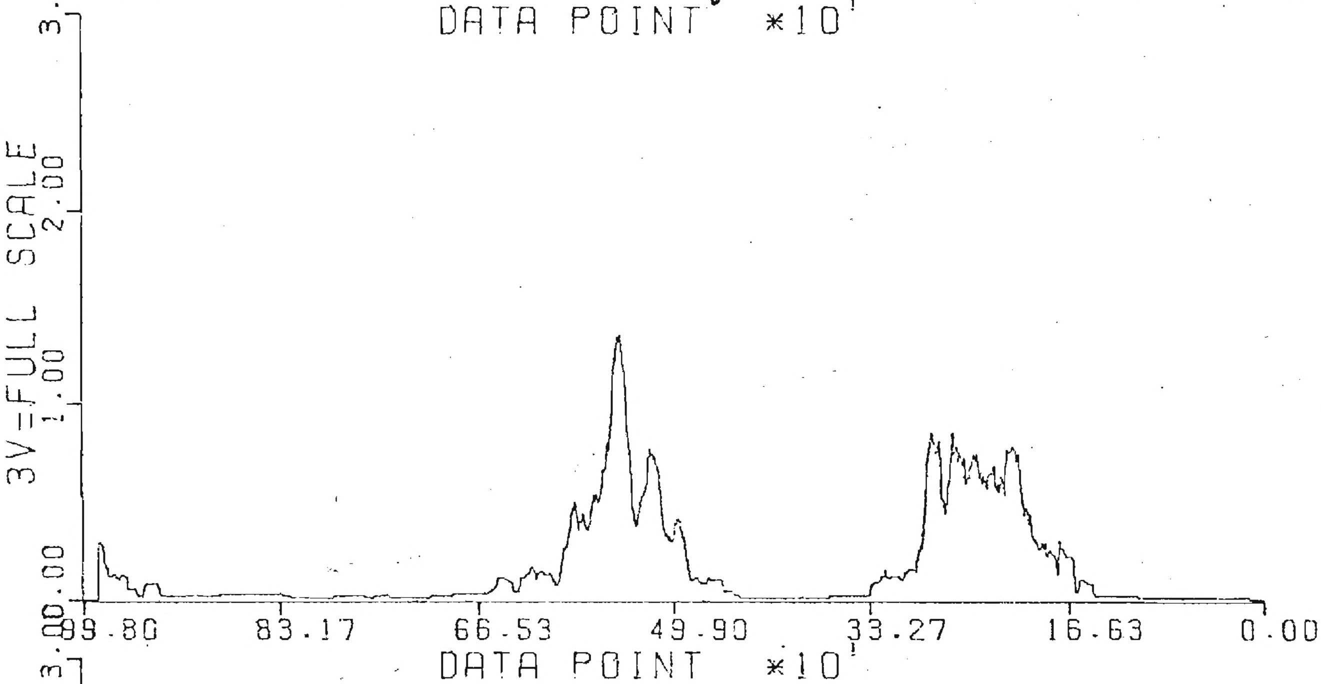
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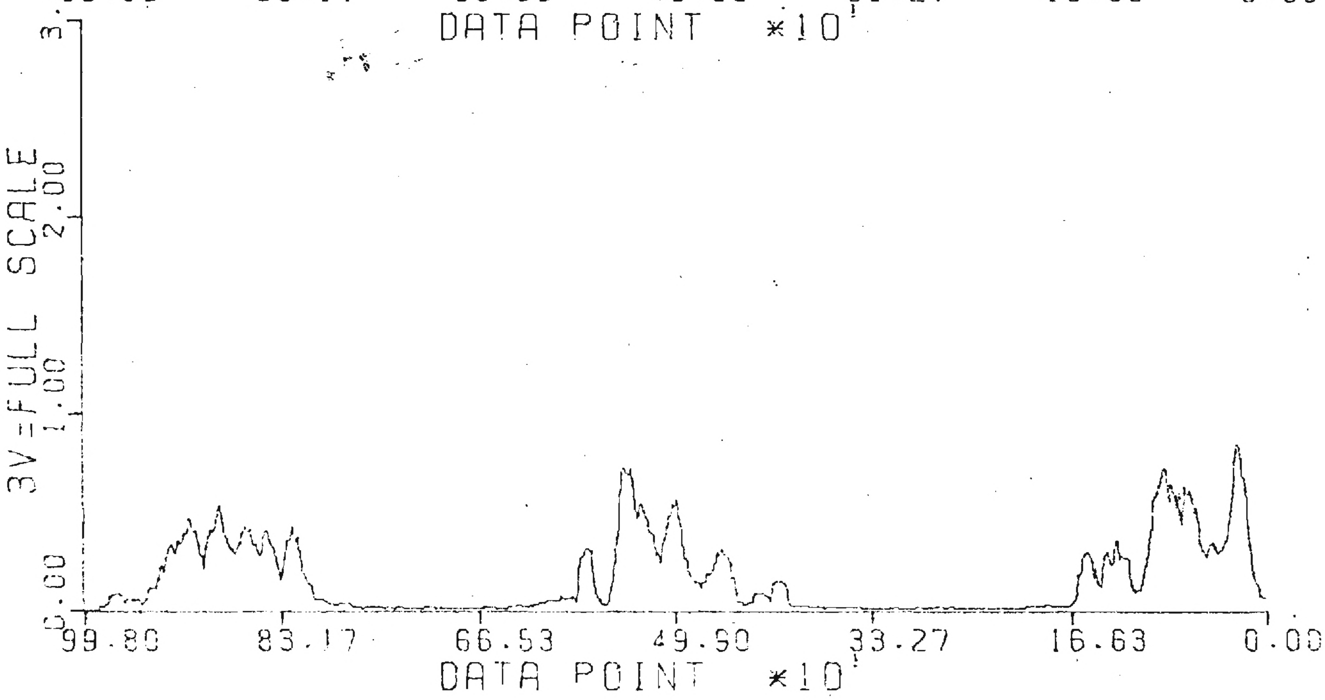
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Figure 7

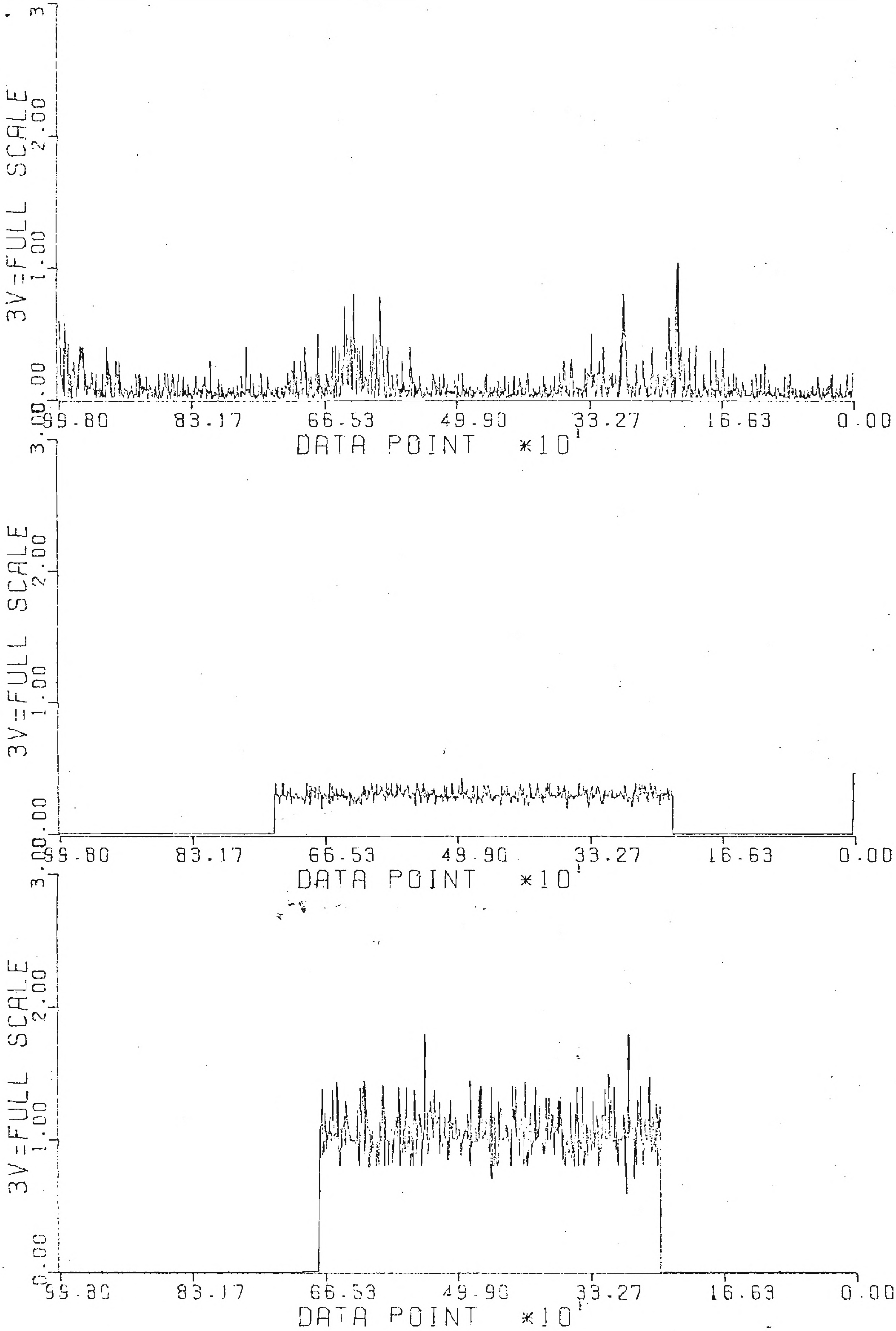
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Figure 8

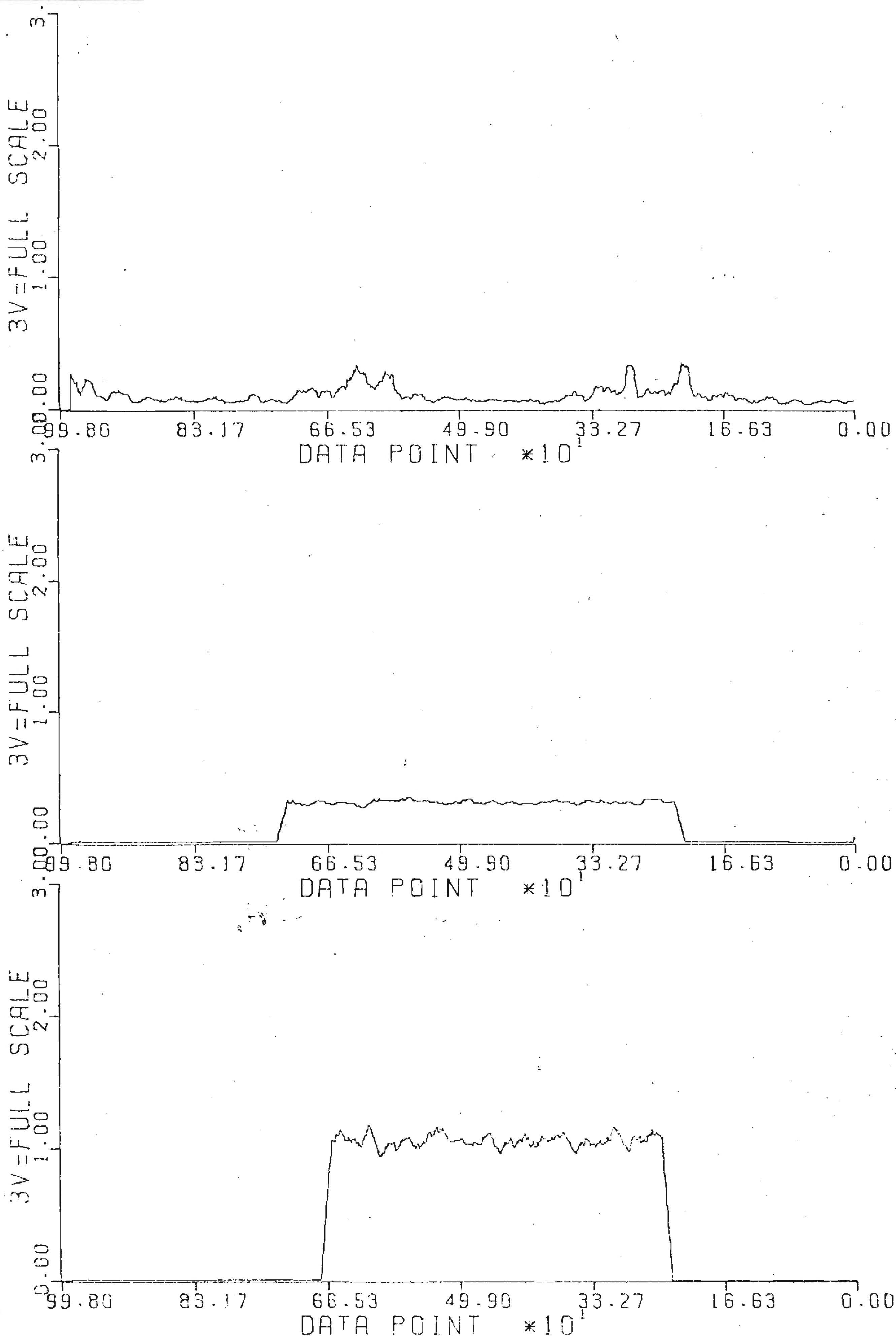
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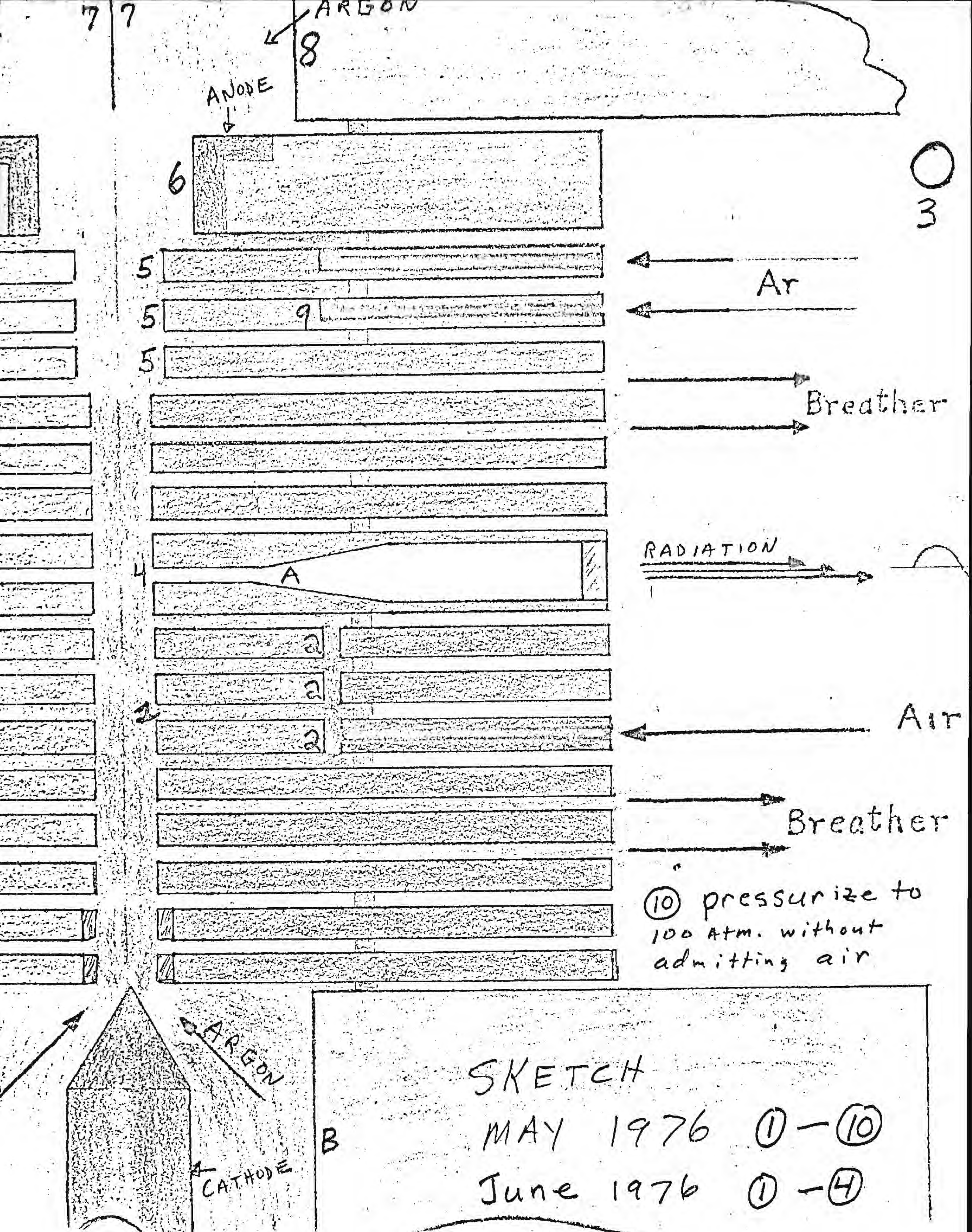
Figure 9



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June 1976 1 – 4


Figure 10